
ASSINIBOINE RIVER WATER QUALITY STUDY

LAKE OF THE PRAIRIES TO THE CITY OF BRANDON

WATER QUALITY MODEL

By Nicole Armstrong
Water Quality Management Section,
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Building for the Future

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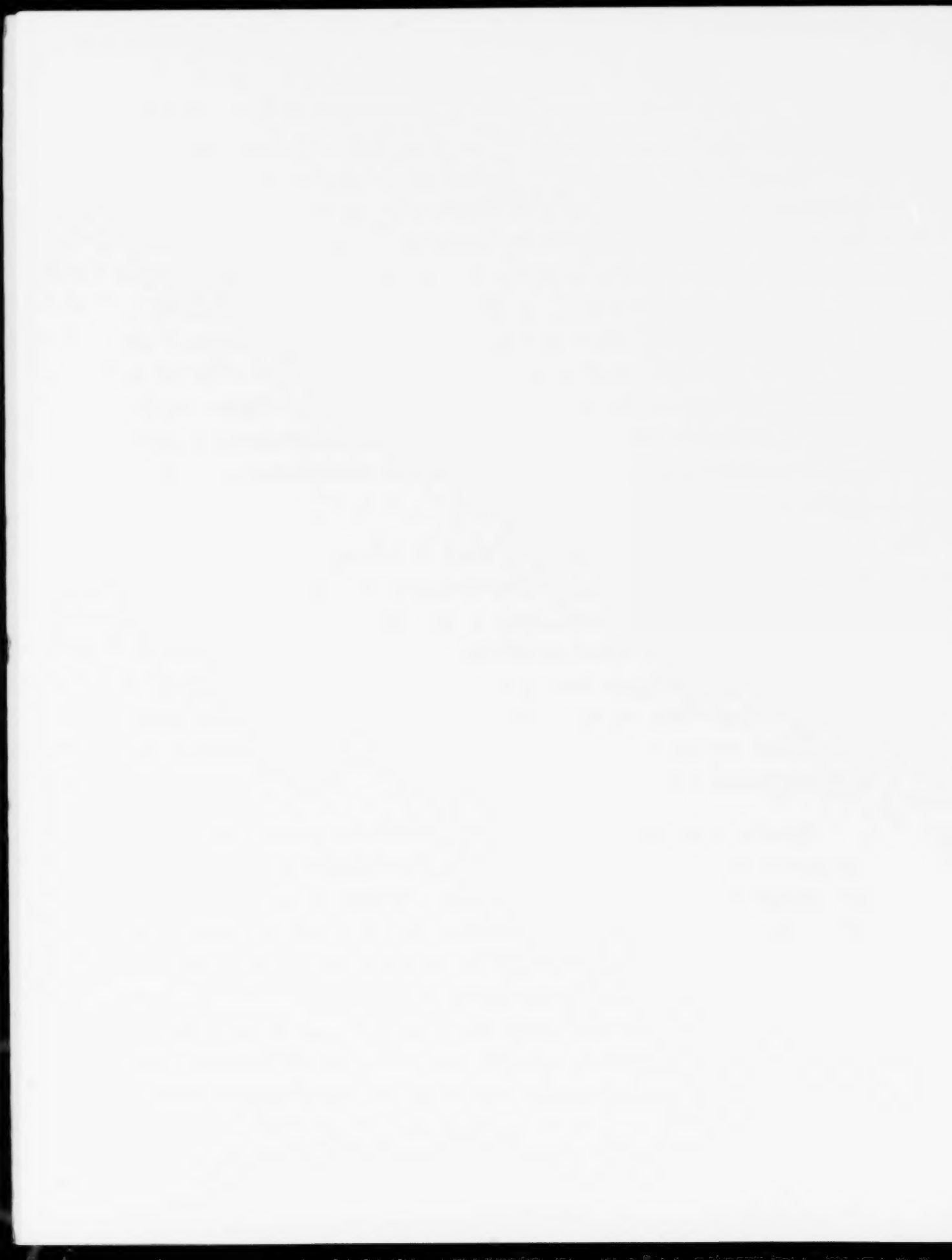
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EXECUTIVE SUMMARY

The Assiniboine River flows from its headwaters in eastern Saskatchewan into and across the western portion of Manitoba to its confluence with the Red River within the City of Winnipeg. Roughly 60 % (24,900 km²) of the relatively large watershed is within the province of Manitoba and drains an area dominated by agriculture and populated with about 800,000 people. The Assiniboine River is used for recreational activities such as boating, canoeing, water skiing, fishing, and swimming and is the drinking water source for the cities of Brandon and Portage la Prairie. The river provides essential habitat for about 40 species of fish and its shoreline supports numerous plant and animal species. Water drawn from the river is used for irrigation and for facilities such as food processing industries. The Assiniboine River is also the recipient of treated effluent from a number of municipal and industrial wastewater treatment facilities.

In response to questions regarding the impact of development along the Assiniboine River, two major studies were undertaken on the lower reaches of the Assiniboine River (Cooley *et al.* 2001a and b, and North/South Consultants Inc. and Earth Tech (Canada) Inc. 2002). Both studies address the effect of nitrogen and phosphorus inputs on the growth of algae and the associated impacts on downstream water uses. However, the reach of the Assiniboine River between Lake of the Prairies and the City of Brandon has received very little attention despite indications that water quality in the downstream portion is greatly dependent on conditions just upstream of Brandon (Cooley *et al.* 2001a).

Therefore, water quality models were developed for the upstream portion of the Assiniboine River between Lake of the Prairies and the City of Brandon with the United States Environmental Protection Agency's QUAL2K model. Between 19 and 12 water quality sampling stations were established along the study reach and were sampled approximately once or twice monthly between May 2001 and July 2003 for general chemistry (pH, conductivity, alkalinity, etc.), nutrients, chlorophyll *a*, and dissolved oxygen. Four water quality models were developed for the Assiniboine River between Lake of the Prairies and the City of Brandon representing three open water seasons (spring, summer and fall), and one ice-covered season. Water quality models described nutrients (total nitrogen and phosphorus, and associated



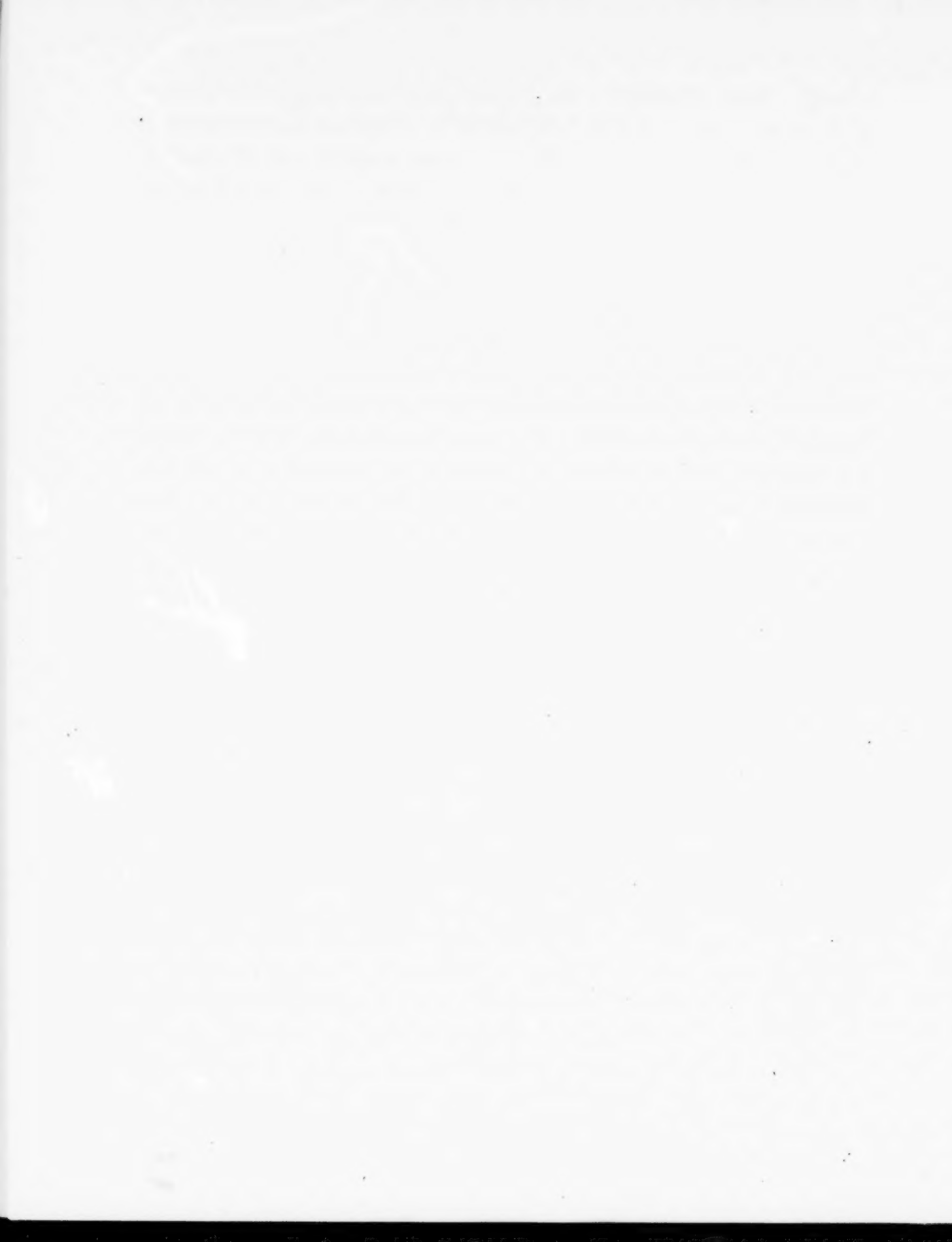
inorganic and organic fractions), dissolved oxygen, chlorophyll *a*, total suspended solids, and conductivity in the Assiniboine River along the study reach. The hydraulic component of the model was developed with the assistance of co-operative education students from Red River College (Winnipeg, Manitoba) and used hydraulic geometry coefficients to describe the relationships between flow, velocity, depth, and width. Each final model was calibrated and tested on at least four independent sampling periods to test the robustness of the model within the range of physical, chemical, and biological conditions observed during the 2001 to 2003 study. Discharge and water chemistry outputs from Lake of the Prairies, tributary inputs from the Qu'Appelle River, Birdtail Creek, and the Little Saskatchewan River, and incremental (runoff) inputs were included in the water quality models.

The success of water quality model calibration as measured by accuracy and precision varied depending upon season and constituent. Generally, calibration was most successful for dissolved oxygen and both inorganic and total phosphorous. Fall and spring periods were modelled with high precision and accuracy. In contrast, summer periods were difficult to model due to the need for reach variable light extinction coefficients and stoichiometric ratios that could not be included in QUAL2K. Periods of transition between ice-covered and ice-free periods such as December and April were also difficult to model due to rapid changes in temperature, aeration, and incremental inflows. The final models provide a mechanism for testing the impact of future changes within the watershed due to climate change, development, or river management. However, future model predictions must be interpreted with caution since conditions outside those tested and calibrated may be controlled by factors not considered during development of these models.

Water quality models were also used to quantify phosphorus and nitrogen loading (both seasonally and longitudinally) to the Assiniboine River from the headwaters at Lake of the Prairies, and the three main tributaries in the upstream reach and to examine variables limiting algal production in the Assiniboine River. Each of the main sources of nitrogen and phosphorus to the water quality model (Lake of the Prairies, the three main tributaries, benthic flux, and incremental inflow (runoff)) was the primary source of nutrients to the upper Assiniboine River during one of the four seasons modelled. Incremental (runoff) and benthic sources dominated nutrient loads in summer while input from Lake of the Prairies was the largest source of nutrients

in the fall. Annual extrapolation of seasonal water quality models suggests that the upper Assiniboine River between Lake of the Prairies and the City of Brandon provides net retention of N and P. Algal biomass in the Assiniboine River was limited primarily by light with phosphorus as the primary nutrient limiting algal biomass during the winter and nitrogen limiting in the open water season.

Water quality data collected as part of model development were examined in comparison to Manitoba's Water Quality Standards, Objectives, and Guidelines. Chronic and acute water quality objectives for total ammonia were met at all times during the study on the Assiniboine River and its tributaries. Acute water quality objectives for dissolved oxygen were met 95 % of the time in the Assiniboine River with all but one of the exceedances occurring during the open water season. Chronic water quality objectives for dissolved oxygen were met 88 % of the time in the Assiniboine River. In the three main tributaries to the Assiniboine River, acute water quality objectives for dissolved oxygen were met during all but one instance each on Birdtail Creek and the Qu'Appelle River. Chronic water quality objectives for dissolved oxygen were met 85 % of the time with the majority of exceptions occurring on the Little Saskatchewan and Qu'Appelle rivers.



SOMMAIRE

Le cours supérieur de la rivière Assiniboine a comme point de départ l'est de la Saskatchewan. De là, la rivière franchit la frontière provinciale et traverse l'ouest du Manitoba jusqu'à la ville de Winnipeg, où elle conflue avec la rivière Rouge. Environ 60 % de ce bassin hydrographique relativement important, soit 24 900 km², se trouve dans la province du Manitoba et draine une zone principalement agricole, habitée par environ 800 000 personnes. La rivière Assiniboine sert à des activités récréatives comme la navigation de plaisance, le canotage, le ski nautique, la pêche et la natation, et alimente en eau potable les villes de Brandon et Portage-la-Prairie. Elle constitue l'habitat essentiel d'environ 40 espèces de poissons et soutient le long de ses rives la vie de nombreuses espèces de plantes et d'animaux. L'eau de la rivière sert à irriguer les champs et est utilisée dans diverses installations comme les industries de transformation des aliments. La rivière Assiniboine reçoit aussi les effluents d'un bon nombre d'installations d'assainissement municipales et industrielles.

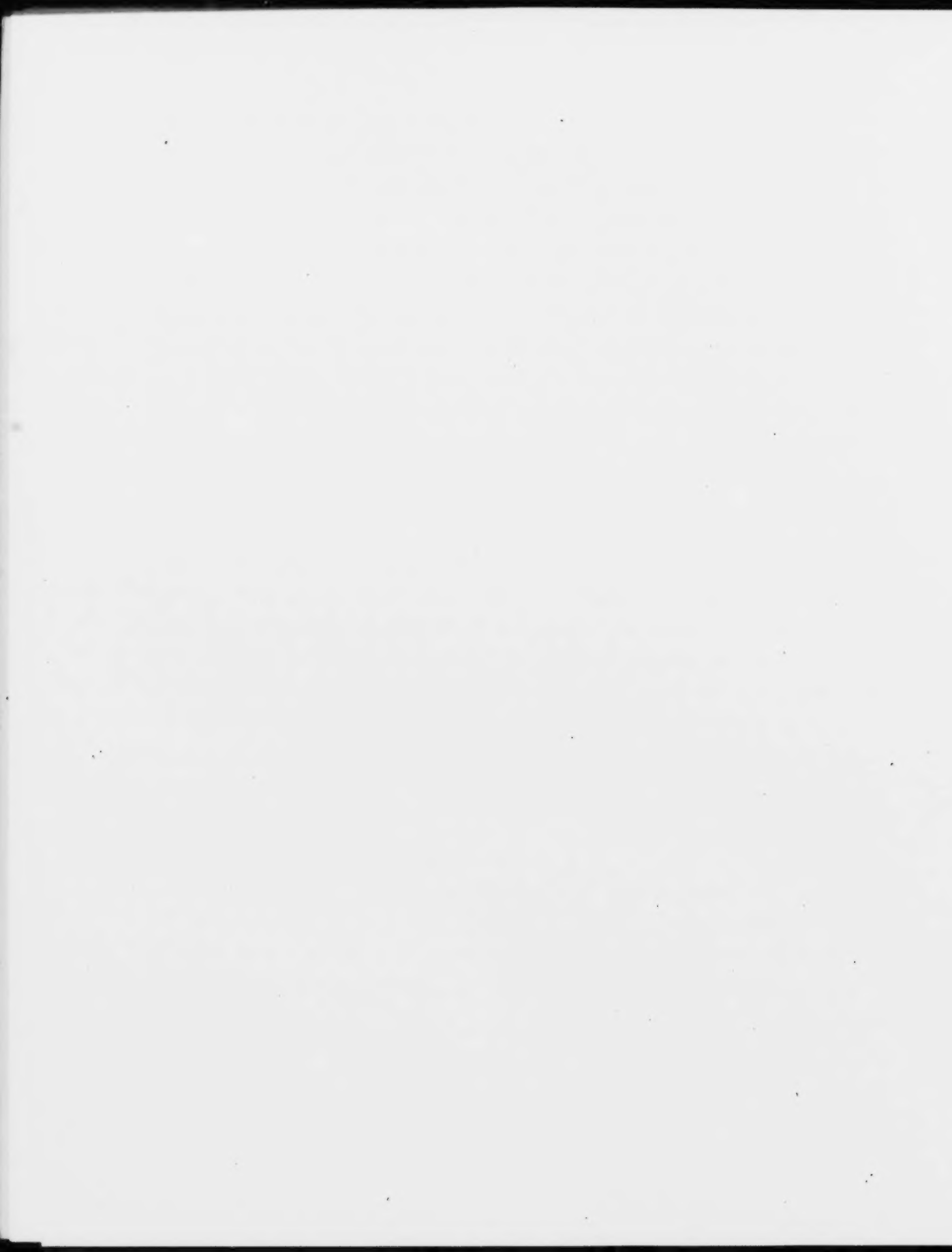
Dans le but de répondre aux questions concernant l'impact du développement le long de la rivière Assiniboine, deux études majeures du tronçon inférieur de ce cours d'eau ont été entreprises (Cooley et autres, 2001 a et b; North/South Consultants Inc. et Earth Tech (Canada), 2002.). Les deux études portent sur les effets de l'apport en azote et en phosphore sur la croissance des algues et sur les conséquences de cet apport sur l'utilisation de l'eau en aval. On a cependant accordé très peu d'attention à la section entre le lac des Prairies et la ville de Brandon, malgré des indications à l'effet que la qualité de l'eau en aval dépend largement des conditions juste en amont de Brandon (Cooley, 2001a).

En conséquence, des modèles d'étude de la qualité de l'eau de l'Assiniboine ont été créés pour le tronçon en amont, entre le lac des Prairies et la ville de Brandon, à l'aide du modèle QUAL2K qu'utilise la Environmental Protection Agency du gouvernement américain. Entre 12 et 19 stations d'échantillonnage de la qualité de l'eau ont été établies le long du tronçon à l'étude. Des échantillons y ont été prélevés une ou deux fois par mois entre mai 2001 et juillet 2003 afin d'en analyser la composition chimique (pH, conductivité, alcalinité, etc.) et les éléments nutritifs, ainsi que la teneur en chlorophylle-a et en oxygène dissous. Quatre modèles ont été élaborés pour cette section entre le lac des Prairies et la ville de Brandon: un pour chaque saison où la surface

est libre de glace (le printemps, l'été et l'automne) et un pour la saison où elle en est recouverte. Les modèles décrivaient les éléments nutritifs (azote et phosphore totaux, et fractions inorganiques et organiques associées), la teneur en oxygène dissous et en chlorophylle-a, la quantité totale de solides en suspension, et la conductivité de l'eau. La composante hydraulique du modèle a été élaborée avec l'aide d'étudiants du programme d'éducation coopérative du collège Red River (Winnipeg, Manitoba), en utilisant des coefficients géométriques hydrauliques pour décrire les relations entre le débit, la vitesse, la profondeur et la largeur. Chaque modèle final a été étalonné et testé pendant au moins quatre périodes indépendantes d'échantillonnage, afin d'évaluer la robustesse du modèle en fonction de la gamme des conditions physiques, chimiques et biologiques observées au cours de cette étude entre 2001 et 2003. Les modèles tenaient également compte du débit et de la composition chimique de l'eau provenant du lac des Prairies, de l'apport des affluents Qu'Appelle, Birdtail et Little Saskatchewan, et des apports de nature ponctuelle (eaux de ruissellement).

Le succès de l'étalonnage, en termes d'exactitude et de précision, variait selon la saison et les constituants. En général, l'étalonnage a eu plus de succès pour l'oxygène dissous ainsi que pour le phosphore total et le phosphore inorganique. Les périodes du printemps et de l'automne ont été modélisées avec beaucoup de précision et d'exactitude. Par contre, la période d'été a été plus difficile à modéliser, étant donné l'obligation de recourir à des coefficients d'extinction de flux lumineux variables et à des rapports stoechiométriques que le modèle QUAL2K ne peut pas accepter. Les périodes de transition entre le gel et le dégel de la rivière, par exemple en décembre ou en avril, étaient également difficiles à modéliser en raison du changement rapide de température, de l'aération et des eaux de venue. Les modèles finaux constituent un mécanisme d'évaluation des répercussions au niveau du bassin hydrologique de modifications futures causées par le changement climatique ou la réalisation de projets de développement, ou encore par la façon dont la rivière est gérée. Les prévisions des modèles, cependant, doivent être interprétées avec prudence puisque des conditions autres que celles qui ont été testées et étalonnées peuvent dépendre de facteurs qui n'ont pas été considérés lors de l'élaboration de ces modèles.

Les modèles ont aussi servi à quantifier la charge en phosphore et en azote dans la rivière par saison et longitudinalement, de son cours supérieur au lac des Prairies et aux trois affluents



principaux du tronçon supérieur, et à examiner les variables limitant la production d'algues dans la rivière. Chacune des principales sources d'azote et de phosphore du modèle [le lac des Prairies, les trois principaux affluents, le flux benthique et l'apport de nature ponctuelle (les eaux de ruissellement)] constituait une source primaire d'éléments nutritifs dans le cours supérieur de l'Assiniboine au cours de l'une des trois saisons modélisées. L'apport ponctuel (eaux de ruissellement) et l'apport benthique produisaient la principale charge en éléments nutritifs au cours de l'été, alors qu'en automne l'apport le plus important provenait du lac des Prairies. L'extrapolation sur une base annuelle des modèles saisonniers suggère que le cours supérieur de la rivière Assiniboine, entre le lac des Prairies et la ville de Brandon, manifeste une rétention nette de l'azote et du phosphore. La biomasse algale de la rivière était limitée principalement par le flux lumineux (le phosphore était le principal élément nutritif limitant la biomasse algale au cours de l'hiver, et l'azote en saison libre de glace).

Les données sur la qualité de l'eau recueillies dans le cadre de l'utilisation du modèle ont été examinées et comparées aux normes, aux directives et aux objectifs officiels du Manitoba en la matière. Les objectifs de qualité de l'eau relatifs à l'ammoniac total, tant en ce qui concerne les effets chroniques que les effets aigus, ont été atteints de façon constante au cours de l'étude sur la rivière Assiniboine et ses affluents. Les objectifs relatifs à l'oxygène dissous dans l'Assiniboine, en ce qui concerne les effets aigus, ont été atteints 95 % du temps (dans tous les cas sauf un, l'excédence s'est produite en période libre de glace); et, en ce qui concerne les effets chroniques, 88 % du temps. Dans les trois principaux affluents de la rivière, les objectifs relatifs à l'oxygène dissous, en ce qui concerne les effets aigus, ont été atteints dans tous les cas, sauf une fois pour chacun des cours d'eau Birdtail et Qu'Appelle; et 85 % du temps en ce qui concerne les effets chroniques (la majorité des exceptions s'étant produites dans les rivières Little Saskatchewan et Qu'Appelle).

TABLE OF CONTENTS

Executive Summary	i
Sommaire	iv
Table of Contents	vii
List of Figures	viii
List of Tables	xiv
Acknowledgments.....	1
1.0 Introduction.....	2
2.0 Description of the Study Area.....	3
3.0 Methods.....	4
3.1 Hydraulic Model	6
3.2 Water Chemistry	8
3.3 Statistics	10
3.4 Climate.....	10
3.5 Rates, Constants, and Coefficients.....	11
4.0 Environmental Setting May 2001 Through July 2003.....	11
4.1 Discharge	11
4.2 Climate.....	13
4.3 Water Chemistry	14
5.0 Water Quality Modelling Methods	19
5.1 Seasonal Water Quality Model Development.....	19
5.2 Overall Water Quality Model Comparison Methods.....	22
6.0 Open Water Model One – Late Spring/Early Summer.....	22
7.0 Open Water Model Two – July/August	28
8.0 Open Water Model Three – September/October	37
9.0 Ice-covered Model One.....	43
10.0 Overall Modelling Results and Discussion.....	50
10.1 Rates, Constants, and Coefficients.....	50
10.2 Nitrogen and Phosphorus Budget in the Assiniboine River	54
10.3 Nitrogen and Phosphorus Limitation in the Upper Assiniboine River	57
11.0 Future Water Quality Model Applications	60
12.0 Conclusions.....	61
13.0 Literature Cited	63
Tables and Figures	67
Appendix A.....	141
Appendix B	142



LIST OF FIGURES

Figure 1. Water quality sampling stations between Lake of the Prairies and the City of Brandon on the Assiniboine River and major tributaries (2001 to 2003).....	68
Figure 2. Discharge during 2001 in the Assiniboine River at Russell, in the Qu'Appelle and Little Saskatchewan rivers, and in Birdtail Creek (note scale compared to Figure 3).....	69
Figure 3. Discharge during 2002 in the Assiniboine River at Russell, in the Qu'Appelle and Little Saskatchewan rivers, and in Birdtail Creek (note scale compared to Figure 2).....	69
Figure 5. Total monthly precipitation for the study period and the Canadian climate normals for Binscarth, Manitoba (Environment Canada 2003b).....	70
Figure 6. Variation in conductivity across the Assiniboine River just downstream of the confluence with the Qu'Appelle River, July 2003.....	71
Figure 7. Change in dissolved oxygen concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	72
Figure 8. Change in chlorophyll a concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	72
Figure 9. Change in conductivity concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	72
Figure 10. Change in total phosphorus concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	73
Figure 11. Change in inorganic phosphorus concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	73
Figure 12. Change in organic phosphorus concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	73
Figure 13. Change in total nitrogen concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	74
Figure 14. Change in ammonia concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	74
Figure 15. Change in nitrite-nitrate concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	74
Figure 16. Change in organic nitrogen concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	75
Figure 17. Change in total suspended solids concentrations during June 5 2002 with distance downstream from Lake of the Prairies.....	75
Figure 18. Change in dissolved oxygen concentrations during May 9 2002 with distance downstream from Lake of the Prairies.....	76
Figure 19. Change in chlorophyll a concentrations during May 9 2002 with distance downstream from Lake of the Prairies.....	76
Figure 20. Change in conductivity concentrations during May 9 2002 with distance downstream from Lake of the Prairies.....	76
Figure 21. Change in total phosphorus concentrations during May 9 2002 with distance downstream from Lake of the Prairies.....	77
Figure 22. Change in inorganic phosphorus concentrations during May 9 2002 with distance downstream from Lake of the Prairies.....	77
Figure 23. Change in total nitrogen concentrations during May 9 2002 with distance downstream from Lake of the Prairies.....	77

Figure 24. Change in organic nitrogen concentrations during May 9 2002 with distance downstream from Lake of the Prairies.....	78
Figure 25. Change in total suspended solids concentrations during May 9 2002 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).....	78
Figure 26. Change in dissolved oxygen concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	79
Figure 27. Change in chlorophyll a concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	79
Figure 28. Change in conductivity concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	79
Figure 29. Change in total phosphorus concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	80
Figure 30. Change in inorganic phosphorus concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	80
Figure 31. Change in organic phosphorus concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	80
Figure 32. Change in total nitrogen concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	81
Figure 33. Change in ammonia concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	81
Figure 34. Change in nitrite-nitrate concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	81
Figure 35. Change in organic nitrogen concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	82
Figure 36. Change in total suspended solids concentrations during July 25 2001 with distance downstream from Lake of the Prairies.....	82
Figure 37. Change in total phosphorus concentrations during August 21 2002 with distance downstream from Lake of the Prairies.....	82
Figure 38. Change in inorganic phosphorus concentrations during August 21 2002 with distance downstream from Lake of the Prairies.....	83
Figure 39. Change in organic phosphorus concentrations during August 21 2002 with distance downstream from Lake of the Prairies.....	83
Figure 40. Change in chlorophyll a concentrations during August 21 2002 with distance downstream from Lake of the Prairies.....	83
Figure 41. Change in chlorophyll a concentrations during August 7 2002 with distance downstream from Lake of the Prairies.....	84
Figure 42. Change in chlorophyll a concentrations during August 8 2001 with distance downstream from Lake of the Prairies.....	84
Figure 43. Change in dissolved oxygen concentrations during July 16 2003 with distance downstream from Lake of the Prairies.....	85
Figure 44. Change in chlorophyll a concentrations during July 16 2003 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).....	85
Figure 45. Change in conductivity concentrations during July 16 2003 with distance downstream from Lake of the Prairies.....	85
Figure 46. Change in total phosphorus concentrations during July 16 2003 with distance downstream from Lake of the Prairies.....	86

Figure 47. Change in inorganic phosphorus concentrations during July 16 2003 with distance downstream from Lake of the Prairies.....	86
Figure 48. Change in total nitrogen concentrations during July 16 2003 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).....	86
Figure 49. Change in organic nitrogen concentrations during July 16 2003 with distance downstream from Lake of the Prairies.....	87
Figure 50. Change in dissolved oxygen concentrations during July 29 2003 with distance downstream from Lake of the Prairies.....	87
Figure 51. Change in chlorophyll a concentrations during July 29 2003 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).....	87
Figure 52. Change in conductivity concentrations during July 29 2003 with distance downstream from Lake of the Prairies.....	88
Figure 53. Change in total phosphorus concentrations during July 29 2003 with distance downstream from Lake of the Prairies.....	88
Figure 54. Change in inorganic phosphorus concentrations during July 29 2003 with distance downstream from Lake of the Prairies.....	88
Figure 55. Change in total nitrogen concentrations during July 29 2003 with distance downstream from Lake of the Prairies.....	89
Figure 56. Change in organic nitrogen concentrations during July 29 2003 with distance downstream from Lake of the Prairies.....	89
Figure 57. Change in dissolved oxygen concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	90
Figure 58. Change in chlorophyll a concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	90
Figure 59. Change in conductivity concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	90
Figure 60. Change in total phosphorus concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	91
Figure 61. Change in inorganic phosphorus concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	91
Figure 62. Change in organic phosphorus concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	91
Figure 63. Change in total nitrogen concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	92
Figure 64. Change in ammonia concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	92
Figure 65. Change in nitrite-nitrate concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	92
Figure 66. Change in organic nitrogen concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	93
Figure 67. Change in total suspended solids concentrations during September 19 2001 with distance downstream from Lake of the Prairies.....	93
Figure 68. Change in dissolved oxygen concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	94
Figure 69. Change in chlorophyll a concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	94

Figure 70. Change in conductivity concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	94
Figure 71. Change in total phosphorus concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	95
Figure 72. Change in inorganic phosphorus concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	95
Figure 73. Change in organic phosphorus concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	95
Figure 74. Change in total nitrogen concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	96
Figure 75. Change in ammonia concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	96
Figure 76. Change in nitrite-nitrate concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	96
Figure 77. Change in organic nitrogen concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	97
Figure 78. Change in total suspended solids concentrations during September 4 2001 with distance downstream from Lake of the Prairies.....	97
Figure 79. Change in dissolved oxygen concentrations during September 4 2002 with distance downstream from Lake of the Prairies.....	98
Figure 80. Change in chlorophyll a concentrations during September 4 2002 with distance downstream from Lake of the Prairies.....	98
Figure 81. Change in conductivity concentrations during September 4 2002 with distance downstream from Lake of the Prairies.....	98
Figure 82. Change in total phosphorus concentrations during September 4 2002 with distance downstream from Lake of the Prairies.....	99
Figure 83. Change in inorganic phosphorus concentrations during September 4 2002 with distance downstream from Lake of the Prairies.....	99
Figure 84. Change in total nitrogen concentrations during September 4 2002 with distance downstream from Lake of the Prairies.....	99
Figure 85. Change in ammonia concentrations during September 4 2002 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).....	100
Figure 86. Change in nitrite-nitrate concentrations during September 4 2002 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).....	100
Figure 87. Change in organic nitrogen concentrations during September 4 2002 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).....	100
Figure 88. Change in dissolved oxygen concentrations during January 2002 with distance downstream from Lake of the Prairies.....	101
Figure 89. Change in chlorophyll a concentrations during January 2002 with distance downstream from Lake of the Prairies.....	101
Figure 90. Change in conductivity concentrations during January 2002 with distance downstream from Lake of the Prairies.....	101
Figure 91. Change in total phosphorus concentrations during January 2002 with distance downstream from Lake of the Prairies.....	102
Figure 92. Change in inorganic phosphorus concentrations during January 2002 with distance downstream from Lake of the Prairies.....	102



Figure 93. Change in organic phosphorus concentrations during January 2002 with distance downstream from Lake of the Prairies.....	102
Figure 94. Change in total nitrogen concentrations during January 2002 with distance downstream from Lake of the Prairies.....	103
Figure 95. Change in ammonia concentrations during January 2002 with distance downstream from Lake of the Prairies.....	103
Figure 96. Change in nitrite-nitrate concentrations during January 2002 with distance downstream from Lake of the Prairies.....	103
Figure 97. Change in organic nitrogen concentrations during January 2002 with distance downstream from Lake of the Prairies.....	104
Figure 98. Change in total suspended solids concentrations during January 2002 with distance downstream from Lake of the Prairies.....	104
Figure 99. Change in chlorophyll a concentrations during December 2001 with distance downstream from Lake of the Prairies.....	105
Figure 100. Change in dissolved oxygen concentrations during December 2001 with distance downstream from Lake of the Prairies.....	105
Figure 101. Change in nitrite-nitrate concentrations during December 2001 with distance downstream from Lake of the Prairies.....	105
Figure 102. Change in total phosphorus concentrations during December 2002 with distance downstream from Lake of the Prairies.....	106
Figure 103. Change in inorganic phosphorus concentrations during December 2002 with distance downstream from Lake of the Prairies.....	106
Figure 104. Change in nitrite-nitrate concentrations during December 2002 with distance downstream from Lake of the Prairies.....	106
Figure 105. Change in total nitrogen concentrations during December 2002 with distance downstream from Lake of the Prairies.....	107
Figure 106. Change in ammonia concentrations during December 2002 with distance downstream from Lake of the Prairies.....	107
Figure 107. Change in dissolved oxygen concentrations during February 2002 with distance downstream from Lake of the Prairies.....	108
Figure 108. Change in chlorophyll a concentrations during February 2002 with distance downstream from Lake of the Prairies.....	108
Figure 109. Change in conductivity concentrations during February 2002 with distance downstream from Lake of the Prairies.....	108
Figure 110. Change in total phosphorus concentrations during February 2002 with distance downstream from Lake of the Prairies.....	109
Figure 111. Change in inorganic phosphorus concentrations during February 2002 with distance downstream from Lake of the Prairies.....	109
Figure 112. Change in organic phosphorus concentrations during February 2002 with distance downstream from Lake of the Prairies.....	109
Figure 113. Change in total nitrogen concentrations during February 2002 with distance downstream from Lake of the Prairies.....	110
Figure 114. Change in ammonia concentrations during February 2002 with distance downstream from Lake of the Prairies.....	110
Figure 115. Change in nitrite-nitrate concentrations during February 2002 with distance downstream from Lake of the Prairies.....	110

Figure 116. Change in organic nitrogen concentrations during February 2002 with distance downstream from Lake of the Prairies.....	111
Figure 117. Change in total suspended solids concentrations during February 2002 with distance downstream from Lake of the Prairies.....	111
Figure 118. Change in ammonia concentrations during April 2002 with distance downstream from Lake of the Prairies.....	111
Figure 119. Change in total phosphorus concentrations during April 2002 with distance downstream from Lake of the Prairies.....	112
Figure 120. Change in inorganic phosphorus concentrations during April 2002 with distance downstream from Lake of the Prairies.....	112
Figure 121. Change in nitrite-nitrate concentrations during April 2002 with distance downstream from Lake of the Prairies.....	112
Figure 122. Change in organic nitrogen concentrations during April 2002 with distance downstream from Lake of the Prairies.....	113
Figure 123. Change in total suspended solids concentrations during April 2002 with distance downstream from Lake of the Prairies.....	113
Figure 124. Change in dissolved oxygen concentrations during January 2003 with distance downstream from Lake of the Prairies.....	114
Figure 125. Change in chlorophyll a concentrations during January 2003 with distance downstream from Lake of the Prairies.....	114
Figure 126. Change in conductivity concentrations during January 2003 with distance downstream from Lake of the Prairies.....	114
Figure 127. Change in total phosphorus concentrations during January 2003 with distance downstream from Lake of the Prairies.....	115
Figure 128. Change in inorganic phosphorus concentrations during January 2003 with distance downstream from Lake of the Prairies.....	115
Figure 129. Change in ammonia concentrations during January 2003 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).....	115
Figure 130. Change in nitrite-nitrate concentrations during January 2003 with distance downstream from Lake of the Prairies.....	116
Figure 131. Change in total suspended solids concentrations during January 2003 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).....	116
Figure 132. Change in modelled inorganic phosphorus concentrations during spring under three outflow scenarios from Lake of the Prairies.....	117
Figure 133. Change in modelled inorganic phosphorus concentrations during fall under three outflow scenarios from Lake of the Prairies.....	117

LIST OF TABLES

Table 1. Water quality station descriptions and locations on the Assiniboine River and tributaries (2001 to 2003).....	118
Table 2. Mean discharge (m^3/s) from Lake of the Prairies, two stations on the Assiniboine River, and the three major tributaries to the upper Assiniboine. Median values are based on weekly data for the time periods 1970 to 1999 (Surface Water Management Section 2003).	119
Table 3: Discharge (m^3/s) at the outlet of Lake of the Prairies, the Assiniboine River, and the three main tributaries, and the resulting incremental inflows and travel times between Lake of the Prairies and the City of Brandon for each sampling period (2001 to 2003).	120
Table 4. Monthly air temperature and precipitation at Binscarth, Manitoba during 2001 to 2003 (Environment Canada 2003b).	121
Table 5. Mean and range of constituent concentrations along the Assiniboine River for each sampling period during the study (2001 to 2003).	122
Table 6. Model accuracy and precision for the June 5 2002 water quality model (* not normally distributed).	126
Table 7. Model accuracy and precision for the June 19 2002 water quality model (* not normally distributed).	126
Table 8. Model accuracy and precision for the July 24 2002 water quality model.	127
Table 9. Model accuracy and precision for the June 13 2001 water quality model (* not normally distributed).	127
Table 10. Model accuracy and precision for the May 9 2002 water quality model (* not normally distributed).	128
Table 11. Model accuracy and precision for the July 25 2001 water quality model (* not normally distributed).	128
Table 12. Model accuracy and precision for the August 8 2001 water quality model (* not normally distributed).	129
Table 13. Model accuracy and precision for July 24 2002 water quality model.	129
Table 14. Model accuracy and precision for the August 7 2002 water quality model (* not normally distributed, ^x outlier removed).	130
Table 15. Model accuracy and precision for August 21 2002 water quality model.	130
Table 16. Model accuracy and precision for the September 19 2001 water quality model (* not normally distributed).	131
Table 17. Model accuracy and precision for the September 4 2001 water quality model.	131
Table 18. Model accuracy and precision for the October 10 2001 water quality model (* not normally distributed).	132
Table 19. Model accuracy and precision for the September 18 2002 water quality model (* not normally distributed).	132
Table 20. Model accuracy and precision for the October 15 2002 water quality model.	133
Table 21. Model accuracy and precision for the January 2002 water quality model.	133
Table 22. Model accuracy and precision for the February 2002 water quality model (^x outlier removed).	134
Table 23. Model accuracy and precision for the December 2002 water quality model (* not normally distributed, ^x outlier removed).	134
Table 24. Model accuracy and precision for the December 2001 water quality model.	135



Table 25. Model accuracy and precision for the April 2002 water quality model (^x outlier removed).	135
Table 26. Model accuracy and precision for the January 2003 water quality model.	136
Table 27. Rates, constants, and coefficients used to model the upper Assiniboine River during the four seasons (2001 to 2003).	137
Table 28. Seasonal fluctuations in benthic fluxes of NH ₄ and inorgP in the four final models for the upper Assiniboine River (2001 to 2003).	138
Table 29. Relative contribution (%) of the four main sources of nutrients modelled in the upper Assiniboine River during each of the four seasons and compared to measured loads at Brandon (2001 to 2003).	139



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1.0 Introduction

The Assiniboine River flows from its headwaters in eastern Saskatchewan into and across the western portion of Manitoba to its confluence with the Red River within the City of Winnipeg. The Assiniboine River watershed is relatively large, encompassing an area of about 41,500 km² (not including the Qu'Appelle and Souris River basins which are usually considered separately). Roughly 60 % (24,900 km²) of the watershed is within the province of Manitoba and drains an area dominated by agriculture and populated with about 800,000 people. The Assiniboine River is used for recreational activities such as boating, canoeing, water skiing, fishing, and swimming. The river provides essential habitat for about 40 species of fish and its shoreline supports numerous plant and animal species. Water drawn from the river is used for irrigation and for facilities such as food processing industries, and is the drinking water source for the cities of Brandon and Portage la Prairie. The Assiniboine River is also the recipient of treated effluent from a number of municipal and industrial wastewater treatment facilities.

In response to questions regarding the impact of development along the Assiniboine River, two major studies were undertaken on the lower reaches of the Assiniboine River (Cooley *et al.* 2001a and b, and North/South Consultants Inc. and Earth Tech (Canada) Inc. 2002). Both studies address the effect of nitrogen and phosphorus inputs on the growth of algae and the associated impacts on downstream water uses. Water quality models were developed for both the reaches with the United States Environmental Protection Agency (EPA) model QUAL2E (Cooley *et al.* 2001a and b, North *et al.* 2003). Together these studies describe the Assiniboine River between the City of Brandon and Headingley (26 km from the Assiniboine River confluence with the Red River). In addition, considerable historical data have been collected on this same reach of the Assiniboine River between the Cities of Brandon and Winnipeg by Manitoba Water Stewardship since the early 1970s (Jones and Armstrong 2001). However, the reach of the Assiniboine River between Lake of the Prairies and the City of Brandon has received very little attention despite indications that water quality in the downstream portion is greatly dependent on conditions just upstream of Brandon (Cooley *et al.* 2001a).

Therefore, the upstream portion of the Assiniboine River between Lake of the Prairies and the City of Brandon was studied with the following objectives: 1) to develop water quality

models for the upstream reach of the river; 2) to examine water quality in comparison to Manitoba's Water Quality Standards, Objectives, and Guidelines (Williamson 2002); 3) to quantify phosphorus and nitrogen loading (both seasonally and longitudinally) to the Assiniboine River from the headwaters at Lake of the Prairies, and the three main tributaries in the upstream reach; and 4) to examine variables limiting algal production in the Assiniboine River.

2.0 Description of the Study Area

The study reach described in this report is the Assiniboine River between Lake of the Prairies (also known as the Shellmouth Reservoir) and the City of Brandon. Lake of the Prairies was created in 1969 to provide downstream flood control protection and was also intended to provide a consistent water supply for downstream users. The reservoir can store up to 477,000 dam³ of water at the spillway crest elevation. The study area includes all of the Foxwarren, Hamiota, and Little Saskatchewan divisions of the Assiniboine River watershed and portions of the Kamsack and Brandon divisions. Terrestrially, the study area includes parts of two Canadian ecozones, the Prairies and the Boreal Plains, and three ecoregions - Aspen Parklands, Mid-Boreal Uplands, and Boreal Transition (Smith *et al.* 1998). The undersized Assiniboine River sits in a broad valley formed about 10,000 years ago when glacial melt water flowed in large quantities through the area. The valley walls are steep (15 to 60 % slope) and range from 50 to 150 m in length with maximum relief from valley wall crest to valley wall floor ranging from 30 to 60 m. The three main tributaries to the Assiniboine River within the study area, the Qu'Appelle River, Birdtail Creek, and the Little Saskatchewan River are also undersized and flow in broad valleys with steep slopes and considerable relief. Imperfectly drained Regosolic soils on river alluvium characterize the valley floors while well drained Black Chernozems developed on strongly calcareous, glacial till derived from limestone, granitic rock and local bedrock shale predominant in the Aspen Parklands. Vegetation in the Aspen Parklands ecoregion, which encompasses most of the watershed, consists primarily of trembling aspen and shrubs in moist areas, and bur oak and grassland communities in drier areas. The Boreal Transition and Mid-Boreal Uplands ecoregions on the northern edge of the watershed are characterized by Dark Grey Chernozemic soils associated with all types of deposits and Gray Luvisolic soils associated with moderately calcareous, fine loamy to clayey till, respectively. Vegetation in these portions of the Boreal Plain ecozone consists primarily of closed stands of trembling aspen with balsam poplar and an

understory of mixed herbs and tall shrubs. Some spruce and balsam fir are present in stands in later successional stages.

Approximately 80 % of the land use within the study area is dedicated to agricultural activities with about 51 % cropland, 26 % grasslands/pasturelands, and 3 % perennial forage (Armstrong 2002). Eleven wastewater treatment facilities for small towns and villages discharge to the Assiniboine River or its tributaries between Lake of the Prairies and the City of Brandon. Only one industrial facility discharges to the Assiniboine River within the study reach. CanAmera Foods, near Russell, Manitoba at the upstream end of the watershed, is an oil seed processing plant that has occasionally discharged effluent from a wastewater lagoon under emergency conditions (subject to approval from Manitoba Conservation).

3.0 Methods

The water quality modelling program QUAL2E (Brown and Barnwell 1987) was used for the first two and half years of this study as the basis for development of a hydraulic model and for the design of the sampling program. In December 2003, a new version of QUAL2E, called QUAL2K, was released by the US EPA (Chapra and Pelletier 2003). QUAL2K, which is implemented within the Microsoft Windows environment, is programmed in the Windows macro language (Visual Basic for Applications) and uses Excel as the graphical user interface. While modelling with QUAL2E is limited to Windows 95, 98, and NT operating systems, QUAL2K can also be executed in a Windows XP operating environment. Therefore, to improve the availability and future usefulness of the upper Assiniboine River water quality model, the modelling framework initially developed in QUAL2E was modified to fit the QUAL2K model.

QUAL2K is similar to QUAL2E in that the river channel is modelled in one dimension and is assumed to be well-mixed vertically and laterally. Both models assume steady state hydraulics, and point and non-point source loads and abstractions are simulated in steady state. However, QUAL2K includes several new elements, some of which were incorporated into the Assiniboine River study. Several additional parameters can be modelled with QUAL2K including pH, alkalinity, inorganic suspended solids, total suspended solids (TSS - see Appendix A for a list of common abbreviations), total organic carbon (TOC), detritus, and both soluble organic nitrogen (N) and phosphorus (P) concentrations. Sediment-water interactions such as

sediment oxygen demand (SOD) and nutrient fluxes are simulated internally in QUAL2K, although as with QUAL2E additional fluxes can also be prescribed. Light extinction is calculated as a function of algae, detritus and inorganic solids while anoxia is incorporated by reducing oxidation reactions to zero at low oxygen levels. Denitrification is also modelled as a first-order reaction that becomes pronounced at low oxygen concentrations. QUAL2K also includes a function for modelling attached algae (periphyton). In contrast to QUAL2E, QUAL2K allows for segmenting of reaches into unequal rather than equally spaced elements. However, since the hydraulic model was developed based on equally spaced elements, model segmentation developed for QUAL2E was maintained for QUAL2K. Finally, while QUAL2E allows several rates to be modified on a reach basis, QUAL2K requires that rates (nitrification and organic N and P mineralization) be held constant throughout the entire model. Since manipulation of rates allowed for enhanced calibration of QUAL2E, the switch to QUAL2K minimized the number of rates that could be manipulated to enhance model accuracy and precision. Therefore, some loss of model accuracy and precision may accompany the switch to QUAL2K. Although several adjustments in model parameters and calibration were required for the switch to QUAL2K, it was anticipated that movement to a model that would be more readily available to future users would be of benefit.

Switching to QUAL2K also impacted the development of a single water quality model for the Assiniboine River from Lake of the Prairies to Headingley since downstream reaches from Brandon to Headingley were modelled with QUAL2E. However, it is expected that model calibration for these downstream reaches could be improved by switching to QUAL2K. During the open water season, model calibration between Brandon and Headingley was not achieved (Cooley *et al.* 2001b, North *et al.* 2003). The complex relationship between dissolved oxygen, nutrients, and algal dynamics may have been better modelled in the downstream reaches with QUAL2K which includes advanced modelling of sediment interactions. The water quality model for the Brandon to Portage la Prairie reach would also benefit from the capability of QUAL2K to model periphyton. Dense periphyton mats just downstream of Brandon played an important role in nutrient dynamics but could not be included in the QUAL2E model. In addition, while input for the QUAL2K model differed from that for QUAL2E, water quality data, rates, constants, and coefficients used for the initial modelling provide enough information to develop a model with QUAL2K.

3.1 Hydraulic Model

A hydraulic model was developed for the Assiniboine River between Lake of the Prairies and the City of Brandon with the assistance of co-operative education students from Red River College (Winnipeg, Manitoba). Historical gauging records from seven Water Survey of Canada and/or Manitoba Water Stewardship stations were obtained for 1975 to the present (Environment Canada 2003a, Surface Water Management Section. 2003). At each station, empirical relationships, in the form of power functions with discharge as the independent variable, were developed as in Leopold and Maddock (1953) such that:

$$V = a Q^b$$

$$D = c Q^d$$

$$W = e Q^f$$

where D is stream depth (m), V is stream velocity (m/s), W is stream width (m), and Q is discharge (m^3/s). The hydraulic geometry coefficients, a , b , c , d , e , and f form the basic hydraulic information for input into QUAL2E and QUAL2K.

While the coefficients provide an excellent description of the hydraulic geometry at a wide range of discharges at the seven gauging stations, they do not provide an indication of changes in hydraulic geometry across the rest of the 455 km study reach along the Assiniboine River. Further examination of the hydraulic coefficients and the cross sections drawn for each hydrometric station indicated that some gauging stations were situated in riffles (*e.g.*, Virden) while others were situated in pools (*e.g.*, St. Lazare) (Halket 2003). Therefore, a pattern of alternating pool and riffle sequences was derived for the 455 km stretch of the river such that travel times for a controlled release (See Appendix B) were consistent with those derived from the hydraulic model. Due to limitations of the QUAL2E model, a maximum of 50 alternating pool and riffle combinations could be modelled. Consequently, the Assiniboine River was divided into 48 hydraulically distinct reaches ranging between 5 and 20 km long, and the coefficients used to describe each reach were input into the water quality model. The 48 reach model structure developed for QUAL2E was maintained in the QUAL2K water quality model.

Discharge in the Assiniboine River between Lake of the Prairies and the City of Brandon consists primarily of headwater inputs from Lake of the Prairies, tributary inputs from the Qu'Appelle River, Birdtail Creek, and the Little Saskatchewan River, and incremental inflows from precipitation runoff. Water is released from the outlet of Lake of the Prairies via a 4.6 m diameter conduit located approximately 3 m from the bottom of the reservoir. Although several other small creeks and rivers discharge to the Assiniboine River between Lake of the Prairies and Brandon (e.g., Arrow River, Gopher Creek, Scissor Creek), examination of limited historical discharge records and observations during this study suggested that these contributions were insignificant.

Discharge records during the period of water quality sampling and modelling were obtained from Environment Canada (2003a) for Birdtail Creek, the Qu'Appelle River at Welby, and for the Assiniboine River at Russell, Miniota, and Brandon. Measurements of conduit and spillway discharges from the outlet of Lake of the Prairies and Lake Wahtopanah (Rivers Reservoir on the Little Saskatchewan River) were obtained for the same periods (Surface Water Management Section 2003). The Birdtail Creek gauging station (Water Survey of Canada) is not operated between November and March. Therefore, the last discharge measurement in October and the first measurement in March were extrapolated between November and February to provide a rough estimate of winter discharge in Birdtail Creek. Winter discharge in Birdtail Creek was expected to be small relative to the Qu'Appelle and Little Saskatchewan rivers during the periods of extrapolation.

Incremental inflows (ungauged tributaries and direct runoff inflow) to the Assiniboine River were estimated for each reach based on the difference between measured discharge on the Assiniboine River at the outlet of Lake of the Prairies, and at Russell, Miniota, and Brandon minus known tributary inputs. Incremental inflows were divided evenly between each river element. In some instances incremental inflows were negative and were then considered abstractions in the water quality model.

Travel times from Lake of the Prairies to the City of Brandon were estimated for each modelled scenario based on headwater discharge from the outlet of Lake of the Prairies, incremental inflows, and tributary inputs from the Qu'Appelle, Birdtail, and Little Saskatchewan

ivers. Travel times reflect the length of time required for a drop of water to travel from Lake of the Prairies to the City of Brandon accounting for channel storage and roughness and are expected to be on average 1.6 times that expected for a flood wave to travel downstream (Halket 2003).

3.2 Water Chemistry

Sixteen stations were selected along the Assiniboine River between the outlet of Lake of the Prairies and the City of Brandon (Figure 1 and Table 1). Three additional stations on major tributaries in this reach of the Assiniboine River (Qu'Appelle River, Birdtail Creek, and the Little Saskatchewan River) were also selected. All stations were selected, where possible, to correspond to Water Survey of Canada or Manitoba Water Stewardship river gauging stations. In addition, station selection was targeted both upstream and downstream of major and minor tributary inputs. River distances between water quality stations were obtained from Prairie Farm Rehabilitation Administration (1980 revised 1990). Water samples were collected at intervals of approximately once or twice per month between May 2001 and January 2003. Additional samples were collected in March, May, June, and July 2003. During each sampling period, water samples were collected from all stations over a one or two-day period. Traditionally, water samples collected as part of a water quality modelling exercise are timed such that only one parcel of water is sampled as it moves from the start to the end of the study reach modelled. Since the time it would take for a drop of water to travel from Lake of the Prairies to the City of Brandon during the study was between 8.3 and 19.5 days, more than one "parcel" of water was sampled during each sampling period.

During the ice-free season (May to November), with the exception of dissolved oxygen (DO), water samples were collected where possible by a weighted sample bottle dropped mid-stream from a roadway bridge. Where stations did not correspond with a roadway bridge, samples were collected with a sampling pole from the shoreline. At all times, DO samples were collected with a sampler designed to minimize the production of oxygen bubbles during collection.

During the period of ice cover (December to April), the number of sampling stations on the Assiniboine River was reduced to nine due to poor winter access at some stations. All three

major tributaries were sampled in winter. Water samples were collected from a hole 20 cm in diameter drilled with a needle bar or ice auger. Ice thickness was also measured during each winter sampling period.

During two sampling trips in July 2003, triplicate samples were collected from all bridge stations to provide an estimate of chemical variability across the stream channel. Samples were collected from the right and left sides of the channel in addition to the routine centre sample. Additional water samples were also collected July 20 2003 from the Assiniboine River outlet at Lake of the Prairies and from the Qu'Appelle River. Samples were compared with those collected July 17 2003 and July 29 2003 to assess the extent of short-term variation in constituent concentrations in headwater and tributary inputs.

Temperature was measured at each site with a kerosene-based thermometer and was recorded along with the time of collection. After collection, water samples were dispersed into various sized bottles. Some samples were preserved with H_2SO_4 . Samples were kept on ice in the dark until delivery at CanTest Laboratory¹ approximately 24 hours later. Chemical analyses were conducted for conductivity, alkalinity, pH, chloride, turbidity, total organic phosphorus (TOP), inorganic phosphorus (as total reactive phosphorus, inorgP), total phosphorus (TP), dissolved phosphorus (DP), particulate phosphorus (PP), total ammonia-N (NH_3), nitrate-nitrite-N (NO_2NO_3), total kjeldahl nitrogen (TKN), DO, biological oxygen demand (BOD), total carbon (TC), total organic carbon (TOC), total inorganic carbon (TIC), total suspended solids (TSS), and phytoplankton biomass (as chlorophyll *a*, chl *a*). Total organic nitrogen (TON) was calculated as the difference between TKN and NH_3 . Total dissolved inorganic nitrogen (DIN) included both NO_2NO_3 and NH_3 . Total nitrogen (TN) was estimated as the sum of TKN and NO_2NO_3 .

Several variables required for water quality modelling were estimated. The relative contribution of inorganic (vs. organic) suspended solids in the water column was estimated as % inorganic (I) = $\text{TIC}/\text{TC} \times 100$. Total inorganic suspended solids (ISS) concentration was estimated as $\text{ISS} = \text{TSS} \times \% \text{I}$. Total suspended organic solids (OSS) were expected to include both living (algae) and non-living solids. Stoichiometric ratios (Chapra and Pelletier 2003) were

¹ CanTest Limited Professional Analytical Services, 675 Berry Street, Winnipeg, Manitoba

used to determine dry weight (D) and the mass of carbon (C), nitrogen (N), and phosphorus (P) based on chl *a* concentrations such that,

$$100 \text{ g D} : 40 \text{ g C} : 8500 \text{ mg N} : 1400 \text{ mg P} : 1000 \text{ mg Chl } a$$

Except where the concentration of algae (mg D/L) was greater than that of OSS, OSS concentration was estimated as $\text{OSS} = \text{TSS} - \text{ISS}$. Where OSS concentration was less than the concentration of algae (mgD/L) then $\text{OSS} = \text{algae mgD/L}$. Detritus as particulate organic matter (POM) was estimated as $\text{POM} = \text{OSS} - \text{algae (mgD/L)}$. Where $\text{OSS} = \text{algae mgD/L}$ then $\text{POM} = 0.01 \text{ mgD/L}$.

Total organic N and P concentrations were measured in the Assiniboine River because they were required for modelling with QUAL2E. However, QUAL2K required dissolved organic nitrogen (DON) and phosphorus (DOP) concentrations. Consequently, DON and DOP concentrations were estimated as total N or P minus inorganic N or P minus particulate organic N or P. Particulate organic N or P concentrations were estimated as the mass of N or P in algae and detritus based on the stoichiometric ratios.

3.3 Statistics

Water chemistry during the ice-free and open water seasons, between 2001 and 2002, and between the right and left sides of the channel in July 2003 were compared with t-tests when data were normally distributed. Otherwise, the non-parametric, Wilcoxon test was used. Mean monthly discharges in the Assiniboine River at Russell, Miniota, and Brandon during 2001 and 2002 were compared with either a paired-t (normal distribution) or signed rank (non-parametric) test. Differences were considered significant when $P < 0.05$.

3.4 Climate

Air temperatures and precipitation amounts were obtained from Environment Canada (2003b). Comparisons between actual temperatures and precipitation received during the study period were made with data from the climate station at Binscarth, Manitoba. Wet and dry bulb

air temperature as well as wind speed were required for the QUAL2K model. Temperatures and wind speed were obtained from the weather station at Shoal Lake in western Manitoba.

3.5 Rates, Constants, and Coefficients

Rates, constants, and coefficients used in the QUAL2K model were based, where available, on the work done by Cooley *et al.* (2001a and b), and North *et al.* (2003) who developed ice-free and ice-covered water quality models for the downstream reaches of the Assiniboine River. Since the overall objective of the Assiniboine River Water Quality Modelling study is to create a single model for the entire river between Lake of the Prairies and Headingley, an attempt was made to maximize consistency between this study and those done on the downstream reaches. However, rates, constants, and coefficients were altered where necessary during model development and calibration. In these instances, rates, constants, and coefficients were varied within the overall ranges suggested by Brown and Barnwell (1987) and Bowie *et al.* (1985). During ice-free periods, re-aeration coefficients were computed for each reach with a combination of the Owens-Gibb, O'Connor-Dobbins, and Churchill formulas as per Chapra and Pelletier (2003). However, during ice-covered periods, the re-aeration coefficient was set at 0.01 per day.

4.0 Environmental Setting May 2001 Through July 2003

4.1 Discharge

In general, during 2001 and 2002, discharge was relatively low in the Assiniboine River and its tributaries (Table 2). At Water Survey of Canada and Manitoba Water Stewardship gauging stations, discharge is characterized based on comparisons with data collected between 1970 and 1999 (http://www.gov.mb.ca/conservation/watres/river_report.html). Lower decile discharges are defined as those that are exceeded 90 % of the time, median discharges are exceeded 50 % of the time, and upper decile discharges are exceeded 10 % of the time. In the Assiniboine River at Russell, discharges were below the median during approximately 80 % of the study period in 2001 and 2002. Discharges were higher on average at Brandon and were below the median during approximately 66 % of the study period. However, 24 and 29 % of the discharges on the Assiniboine River at Russell and Brandon, respectively, were below the lower

decile suggesting that discharges at Brandon were slightly more extreme than at Russell with relatively more lower and upper decile discharges. Discharge was also relatively low on the Qu'Appelle River during 2001 and 2002, with about 66 % falling below the median. Overall, the study period was characterized by below median discharge since the majority of higher discharge on the Assiniboine and Qu'Appelle rivers occurred prior to the start of water chemistry sampling in May 2001 (Figures 2 and 3).

Travel times from Lake of the Prairies to the City of Brandon ranged between 9.7 to 19.5 days during the 31 periods sampled in 2001 and 2002 (Table 3). Travel times to Brandon were strongly negatively correlated with discharge on the Assiniboine River at Russell (Kendall's Tau -0.6775 , $P < 0.0001$) indicating that longer travel times were associated with lower discharge at Russell. Of the three main tributaries, only discharge from the Qu'Appelle River at Welby was correlated with travel time to Brandon (Kendall's Tau -0.4876 , $P = 0.0001$) although the correlation was weaker than with discharge at Russell. Discharge in the first 40 km of the 455 km river reach (including headwater discharge from the outlet of Lake of the Prairies but excluding tributary discharges) had the greatest influence on overall travel times from Lake of the Prairies to Brandon during the study period.

Relative contributions to discharge in the Assiniboine River from the Qu'Appelle and Little Saskatchewan rivers and from headwater inputs at the outlet of Lake of the Prairies varied throughout 2001 and 2002 (Figures 2 and 3). Gauged discharge at Russell was used to estimate outflow from the outlet of Lake of the Prairies since only estimates of discharge based on gate settings were available from the dam. At different times, each of the sources contributed over 50 % and as much as 86 % of the discharge to the Assiniboine River. Relative contributions to the Assiniboine River from each source also dropped to as low as 5 % during 2001 and 2002. Annual mean contributions to discharge in the Assiniboine River during 2001 and 2002 from the headwaters, and the Qu'Appelle and Little Saskatchewan rivers were remarkably similar at between 27 and 29 % in 2001 and between 29 and 32 % in 2002. Mean annual contributions from Birdtail Creek were considerably less at approximately 15 % and 10 % in 2001 and 2002, respectively. Given that the headwaters from the outlet of Lake of the Prairies and the Qu'Appelle and Little Saskatchewan rivers each contributed a significant proportion of discharge to the Assiniboine River on varying occasion during some portion of the study, it was expected

that their associated chemical and biological characteristics at these times could have had a dominant influence on downstream Assiniboine River characteristics. In contrast, Birdtail Creek was expected to have had a small influence on downstream water chemistry because of its relatively small contribution to discharge in the Assiniboine River.

4.2 Climate

Air temperatures during the study period at Binscarth, Manitoba were relatively close to the climate normals for 1971 to 2000 (Table 4 and Figure 4). The winter of 2001 to 2002 was slightly warmer than normal which may have resulted in later and generally thinner ice formation on the Assiniboine River. However, March through May 2002 was slightly cooler than normal suggesting that ice may have persisted later than normal on the Assiniboine River. Similarly, after a relatively mild to normal winter during 2002 to 2003, February and March 2003 were considerably cooler than normal, perhaps resulting in an overall greater ice thickness and a later thaw date. Overall, temperatures during the ice-free seasons were close to the climate normals, but with slightly cooler springs and falls, and slightly warmer summers. Air temperatures directly influence water temperatures and can therefore impact not only diurnal variations in DO, but also rates of biological and chemical functions in the Assiniboine River.

Total precipitation received during the study period of January 2001 to July 2003 (1241 mm) was remarkably close to the climate normal for 1971 to 2000 (1207 mm). However, while total precipitation received was similar to the climate normal for Binscarth, Manitoba, the temporal distribution of the actual precipitation received varied considerably (Figure 5). Except for the five months with extremely high amounts of precipitation relative to the climate normal, the remaining 22 months had precipitation at or below normal. Precipitation between August 2001 and May 2002 was often well below to normal, amounts that likely resulted in a prolonged period of reduced runoff to the Assiniboine River. Although large amounts of precipitation occurred in June and August 2002, these were followed by below normal precipitation events for the rest of the open water season. High snowfall in December 2002 and large amounts of both snow and rain in April 2003 likely lead to considerably runoff to the Assiniboine River in spring 2003. While precipitation is not a direct input to the QUAL2K water quality model, precipitation patterns can help explain the variation in incremental inflows used in the model.

4.3 Water Chemistry

4.3.0 Objectives

Manitoba Water Quality Objectives for total ammonia are based on temperature and pH (Williamson 2002). In general, ammonia toxicity increases with pH and temperature, and different objectives apply over various averaging durations (30 days, 4 days, and 1 hour) such that aquatic organisms are protected against chronic and acute effects of toxicity. Water samples collected during all seasons at all stations on the Assiniboine River and its tributaries were well below chronic and acute objectives. Total ammonia concentrations during the study ranged between 0.005 and 1.200 mg/L whereas the most stringent objectives ranged from 0.503 to 8.751 mg/L.

Dissolved oxygen objectives are based on water temperature to protect the early to mature stages of fish species with more stringent objectives applying when early life stages are present. Different objectives also apply depending on the presence of cold water (whitefish and trout) versus cool water (walleye and pike) species. Since the Assiniboine River is inhabited by cool water fish, cool water objectives were applied. As with ammonia, DO objectives differed depending on the averaging duration (30 days, 7 days, instantaneous minimum) to provide consideration of both chronic and acute exposure.

At all sites on the Assiniboine River from the outlet at Lake of the Prairies to the City of Brandon between May 2001 and June 2003, acute DO objectives were exceeded 5.1 % of the time (24 out of a total 447 samples). Only one violation of the acute objective occurred during the ice-covered season (January 2002 at PTH #21 Bridge). Most of the remaining exceedances occurred during the summer of 2001 with most stations having DO concentrations below the acute objectives during the June 26 to 27th, 2001 sampling period. Scattered exceedances occurred throughout the rest of the summer of 2001 with no clear patterns of decreasing downstream DO concentrations. Detectably ($P < 0.0124$) warmer air and water temperatures during 2001 as compared to 2002 may have contributed to the relatively low DO concentrations in the summer of 2001.

Dissolved oxygen objectives for chronic fish exposure were violated 12.1 % of the time at all sites on the Assiniboine River from the outlet at Lake of the Prairies to the City of Brandon between May 2001 and June 2003 (54 out of a total 447 samples). As with the acute exposure objectives, chronic exposure objectives were violated primarily during the open water season. Only two exceedances occurred during the ice-covered season (January 2002 at PTH #21 and Trans Canada Highway bridges). Exceedances occurred primarily during the summer of 2001, but were scattered throughout the summer of 2002 as well.

At stations on the three main tributaries to the Assiniboine River, DO objectives for acute exposure were rarely violated. Only one instance each on Birdtail Creek and the Qu'Appelle River, and three instances on the Little Saskatchewan River occurred during the open water season. Chronic exposure objectives were violated about 15 % of the time (16 occurrences out of a total 105 samples) with the majority occurring at the stations on the Little Saskatchewan and Qu'Appelle rivers. Relatively high DO concentrations in the tributaries probably helped to maintain adequate DO concentrations in the Assiniboine River during the study period.

4.3.1 Differences Across Years and With Ice-Cover

As expected, the presence of ice cover had a detectable impact on variables in the Assiniboine River (Table 5). During periods of ice cover, DIN concentrations (NH_3 and NO_2NO_3) were 2 to 3 times higher ($P < 0.0001$) than during periods of open water. A seasonal pattern of higher DIN concentrations during winter has been well documented and explained by a lack of N leaching and increased biological uptake during the growing season (Willett *et al.* 2004, Arheimer and Liden 2000). In contrast, TON concentrations were about 1.3 times higher during periods of open water compared to ice covered conditions ($P = 0.0023$). Total, particulate, and inorganic phosphorus concentrations were also about 1.5 to 2 times higher during the open water compared to the ice-covered season. Additionally, chl *a* concentrations were also almost twice as high during the open water season compared to under ice-cover ($P < 0.0001$). However, DP and DO concentrations were not detectably different between the seasons ($P > 0.05$). Mean water temperature was about 14 degrees higher during the open water season and since warmer water holds less oxygen, the lack of a detectable difference in DO concentrations between seasons may be in part due to an increase in aeration during open water

seasons offset by a reduction in biological processes that consume oxygen in winter. Significantly higher pH, color, turbidity, and TSS were also measured during the open water season ($P = 0.0001$) while conductivity, TDS and both total and bicarbonate alkalinity were higher during the ice covered period ($P < 0.0049$). Differences in water chemistry observed during open water compared to the ice-covered season suggested that biological, chemical, and physical processes varied between the two seasons. Therefore, separate water quality models, with unique rates, constants, and coefficients were derived for the ice-covered and open water seasons in the Assiniboine River.

In contrast to the main stem of the Assiniboine River, differences in water chemistry between ice-covered and open water seasons at the outlet of Lake of the Prairies were less obvious. Since this station remained ice-free throughout the study, differences were expected to result in part from differences in temperature between the two seasons. Some particulate and organic fractions such as particulate and organic P, turbidity, and TOC were 1.2 to 4 times higher during the spring/summer/fall period compared to winter ($P < 0.02$). In contrast, DO was detectably higher during winter ($P < 0.0001$). Differences between ice free and ice-covered samples were likely due to the ability of cooler water to hold more DO than warmer water since water at this station was aerated considerably after passing through the conduit at the outlet of Lake of the Prairies and samples were collected from this station at approximately the same time during the entire study.

Interestingly, NO_2NO_3 concentrations were also considerably higher during winter at the outlet of Lake of the Prairies with mean concentrations about three times higher than during the spring/summer/fall period ($P = 0.03$). Since TON and NH_3 were not detectably different between the two seasons ($P > 0.45$), higher NO_2NO_3 concentrations could result in an increased headwater N load to downstream reaches of the Assiniboine River during winter. Higher winter NO_2NO_3 concentrations may have resulted from a combination of 1) winter stratification in eutrophic Lake of the Prairies resulting in reduced DO concentrations and an accumulation of NH_3 due to decomposition and sediment release, and 2) high rates of nitrification occurring in the well-aerated and rocky, shallow stream bed that exists just downstream of the dam. Wetzel (1983) observed increases in NH_3 concentrations due to winter stratification elsewhere in North America and high rates of nitrification are well documented on aerated and rocky, shallow

stream beds (Thomann and Mueller 1987). Fortin and Gurney (1997) studied nutrients in Lake of the Prairies during the early 1990s and sampled the reservoir just upstream of outlet of Lake of the Prairies. Their work did not indicate higher NH_3 concentrations during winter but samples were collected at mid-depth (< 6.3 m), considerably shallower than the depth at which winter declines in DO were occasionally observed to occur (> 8 m).

Water chemistry during the open water season at all stations on the Assiniboine River differed slightly between 2001 and 2002. Some differences were expected since average air temperatures were about 2.3 degrees warmer on average during 2001 as compared to 2002 ($P < 0.0001$). For example, water temperatures were also approximately 2 degrees warmer during the open water season in 2001 compared to 2002 ($P = 0.0124$). Other differences in water chemistry may have been related to higher average discharge in the Assiniboine River during 2001 compared to 2002 ($P < 0.031$). For example, conductivity was higher during 2002 compared to 2001 perhaps due to the concentration of chemical constituents in the lower discharge year ($P = 0.001$). Chlorophyll *a* concentrations were also about two times higher during 2002 compared to 2001 ($P = 0.0063$). Lower water levels and increased light penetration throughout a shallower water column could enhance biomass however, no detectable differences were observed in turbidity measurements. Nonetheless, increased inorganic nutrient uptake by the higher algal biomass in 2002 may have lead to reduced NH_3 and inorgP concentrations compared to 2001 ($P < 0.0004$). Total precipitation amounts during the 2001 and 2002 open water seasons were remarkably similar at 300 and 307.7 mm, respectively, suggesting that differences in particulate P, C, and N were not related to differences in runoff. Overall, while differences in water chemistry between 2001 and 2002 were detected statistically, relatively percent differences were generally small, with an average difference of about 40 % between the two years.

Similarly, some differences in water chemistry between the ice-covered seasons of 2001 to 2002 and 2002 to 2003 were detected statistically. Concentrations of chl *a*, TP, TOP, PP, TN, TON, PN, DO, TSS, and turbidity were all detectably higher during the 2002 to 2003 winter season ($P < 0.0031$). Some of the lowest DO concentrations were observed in January 2002, lowering the average considerably for that year. It is unlikely that changes in aeration lead to the low concentrations since the low DO concentrations in January 2002 were preceded and followed by relatively higher concentrations, despite continual ice-cover from December to

April. Relatively high chl *a* concentrations in December of 2001 may have undergone decomposition during January 2002 leading to lowered DO concentrations. However, a similar phenomenon was not observed in January 2003 despite elevated chl *a* concentrations in December 2002. NH₃ and TDS concentrations were detectably higher during the 2001 to 2002 winter season although differences were small at 34 and 9 %, respectively ($P < 0.03$). Differences between the two ice-covered seasons were generally larger than those observed between the two open water seasons with an average difference of about 98 %. Despite these differences, data collected during the two years was used interchangeably to develop and calibrate the water quality model. Efforts focused on separating sampling events based on discharge and presence/absence of ice-cover.

4.3.2 Variation in Headwater and Tributary Inputs

Nitrogen and P concentrations varied considerably between sampling periods at the outlet from Lake of the Prairies. Ammonia and NO₂NO₃ concentrations between sampling periods fluctuated by as much as 0.019 and 0.014 mg per day, respectively. Daily differences in inorgP and TOP were as much as 0.008 and 0.011 mg, respectively. Daily fluctuations were most evident for TON concentrations, which varied up to 0.26 mg/day between sampling periods. These observations suggested the assumption of steady conditions over the travel time from Lake of the Prairies to Brandon (at least 9.7 days) required for headwater inputs to the QUAL2E and QUAL2K models was not met. Time of travel from Lake of the Prairies to the City of Brandon was as much as 19.5 days yet nutrient inputs from Lake of the Prairies were still considered to be at steady state in the water quality model. In reality, nutrient concentrations could have varied between 0.165 to 5.6 mg/L over the up to approximately 20 days included in the model run.

Similarly, tributary inputs of N and P to the Assiniboine River varied between sampling periods. Maximum daily fluctuations in the Little Saskatchewan River were estimated as 0.099 and 0.019 mg/d of NO₂NO₃ and NH₃, respectively. Daily differences in TON were highest in the Qu'Appelle River, reaching a maximum of 0.525 mg/day. Maximum daily fluctuations of organic and inorganic phosphorus in the Qu'Appelle River were slightly higher than those observed at the outlet of Lake of the Prairies (0.015 and 0.010 mg/day, respectively). As with headwater inputs from the outlet of Lake of the Prairies, large daily fluctuations in nutrient

concentrations from tributaries suggested that inputs to the Assiniboine River could have varied dramatically during the modelled period. Clearly, the assumption of steady state conditions for both headwater and tributary inputs was not met in the Assiniboine River water quality models.

4.3.3 Variability Across the Assiniboine River

Based on samples collected in July 2003, differences between right and left bank water chemistry were observed at only one station on the Assiniboine River, just downstream of the confluence with the Qu'Appelle River. Distinct stratification across the stream channel was observed for many variables at this one station including conductivity (Figure 6). However, when samples collected from the right and left banks at all 10 (July 29 to 30th) or 11 (July 16 to 17th) stations on the Assiniboine River were compared, no overall differences were detected in any of the chemical variables ($P > 0.05$). Except for just downstream of the confluence with the Qu'Appelle River, the Assiniboine River appeared to be well-mixed across the channel at all stations during July 2003.

5.0 Water Quality Modelling Methods

5.1 Seasonal Water Quality Model Development

Water quality models were developed and calibrated for four seasons including three during periods of open water (Spring/Summer, Summer, and Fall) and one during the period of ice-cover. The spring/summer period was from May 1st to July 24th, the summer period was from July 24th to August 31st, and the fall period was from September 1st to October 31st. Sampling periods identified for development and calibration of the water quality model were selected from the 31 sampling events conducted during 2001 and 2002. Sampling periods were identified throughout the study by the first date in which water sampling occurred (*i.e.*, the initial modelling period for the Spring/Summer model was called June 5 2002 because water sampling occurred on June 5 and 6, 2002). In general, scenarios were chosen such that discharges from the outlet of Lake of the Prairies and the three main tributaries remained relatively constant throughout the modelled period (*i.e.*, the time required for a drop of water to travel from Lake of the Prairies to the City of Brandon). A trial and error process with manipulation of rates,

constants, and coefficients was used to achieve model calibration for the initial models for each of the four seasons.

Model calibration was assessed by calculating and evaluating model accuracy and precision. Percent differences between observed and predicted concentrations at each station along the study reach for a given time period were calculated and averaged to provide an assessment of model accuracy. Consequently, the percent difference could be low but might represent the mean of model predictions both significantly higher and lower than the observed concentrations. The relationship between observed and predicted concentrations was examined with linear regression and provided an estimate of the precision of the model. Since the range of observed and predicted concentrations can impact the strength of the regression equation (Hakason *et al.* 2003), some variables may appear to be predicted more precisely because the data set contains a wide range of concentrations.

Sampling events not used for the initial models were used to test the four calibrated seasonal models. Initially, test models were run with the same constants, rates, and coefficients used in the calibrated models. Only climate, hydraulic (discharge) and water quality (initial, incremental, tributary) data were updated to correspond with the test periods. Tested models were then calibrated with the same trial and error process used for the initial model to determine which rates, constants, and coefficients required modification to improve model predictions. After each test model was manipulated to improve model calibration, the initial model and all test models for a season were assessed to determine which combination of rates, constants, and coefficients combined to produce a model that provided the best overall prediction of Assiniboine River water quality during that season. A final water quality model was then chosen to represent the season. The sample period that had the most constituents with statistically detectable ($P < 0.05$) relationships between observed concentrations and those predicted with the final model was used to develop prediction intervals (Moore and McCabe 1989) around the regression equations. If critical constituents such as DO were not well modelled during the sampling period of choice (*i.e.*, with a detectable relationship between observed and predicted concentrations), a regression equation was selected from one of the remaining sampling periods such that prediction intervals could be established. Regression equations and prediction intervals were then applied to a new sampling period that had not been used to develop the initial, test, or

final models to determine what percentage of the observed concentrations fell within the prediction intervals. Prediction intervals will be used in modelling future scenarios on the Assiniboine River (*i.e.*, increased or decreased discharge through the outlet of Lake of the Prairies, or impact of discharges to surface water) to determine the range of concentrations that might be expected for a particular scenario.

Variable concentrations below laboratory method detection limits proved difficult for model calibration. At times, NH_3 , NO_2NO_3 , and TKN concentrations were below method detection limits. Since concentrations of TON and TN depend on these N fractions, model calibrations for both were also impacted. Linear regression analyses were weak or not possible when a large percentage of observed concentrations across the study reach were below detection limits. Percent mean differences were also often artificially increased when values below detection were compared to model predicted values of zero. Consequently, when observed concentrations were below detection limits, model calibration was based on the assumption that any model result below the detection limit was within the range of observed concentrations.

A conservative constituent, conductivity, was used to assess basic model performance (independent of rates, constants, and coefficients). Conservative constituent concentrations are influenced by external sources and dilution but do not decay or interact with other constituents. Observed conductivity concentrations followed a predictable pattern across the study reach and were subsequently modelled with excellent accuracy and precision for most sampling periods. Although modelled concentrations predicted variation due to tributary inputs, small fluctuations in conductivity between stations were not predicted. Small scale, between-station fluctuations may have been due to local inflow that was not included in the model. However, since sample collection involved several, rather than one, parcel of water moving downstream from Lake of the Prairies to the City of Brandon, between-station fluctuations in conductivity were not entirely unexpected.

Sample outliers were also identified based on changes in conductivity. In some cases, the conductivity of samples collected in the Assiniboine River immediately downstream of the confluence with the Qu'Appelle River and/or Birdtail Creek were more consistent with measurements from the tributary rather than those expected in a well mixed sample. Given that

the Assiniboine River stations were only a few hundred metres downstream of the confluences, it was expected that a fully mixed sample was not always collected. Therefore, conductivity at the Assiniboine River stations immediately downstream of the Qu'Appelle River and Birdtail Creek confluences were compared with those measured in the tributary and subsequent downstream stations. Samples that were determined to be non-homogenous were removed from the modelling exercise.

5.2 Overall Water Quality Model Comparison Methods

The four final seasonal models were used to gain a better understanding of nutrient dynamics in the upper Assiniboine River. Relative contributions of the four main sources of nutrients (headwaters at Lake of the Prairies, three main tributaries, incremental inflows or runoff, and sediment fluxes) to the upper Assiniboine River were compared. Sediment nutrient fluxes were estimated with model derived and user input data. Model-derived wetted perimeter and prescribed reach lengths were used to determine the total area of the sediment. Sediment area was multiplied by the nutrient flux for each reach and then summed to determine total daily flux from the sediments to the upper Assiniboine River.

Nutrient limitation in the Assiniboine River across seasons and along the study reach was assessed with molar TN:TP ratios, model derived algal growth limitation factors, and longitudinal patterns in N and P concentrations. The QUAL2K water quality model estimates algal growth limitation factors for nitrogen, phosphorus, and light allowing model derived estimates of N vs. P vs. light limitation along the study reach. Growth limitation factors vary between one and zero with zero representing maximum limitation and one representing no limitation. Since light limitation varies diurnally as incoming solar radiation changes, hourly N, P, and light growth limitation factors were compared for the four final models representing winter, spring, summer, and fall. During periods of overnight darkness, light was always the most limiting variable thus only periods of daylight were examined.

6.0 Open Water Model One – Late Spring/Early Summer

An initial open water model was developed and calibrated for the time period beginning June 5, 2002. Discharge from Lake of the Prairies was at the lowest observed during the entire

study period (2001 to 2003) at $1.4 \text{ m}^3/\text{s}$ while discharge contributed from the Qu'Appelle River was the sixth lowest observed during the study period. Incremental inflows were similar to the median observed for during the study. In all, time of travel from Lake of the Prairies to Brandon was the fifth slowest (16.2 days) for the study period (Table 3).

Three different time periods were used to test the calibrated model and included June 13 2001, June 19 2002, and July 24 2002 (Table 3). Discharges during the June 19 2002 period was similar to those observed for the initial model development and calibration time period (June 5 2002) with extremely low discharge from Lake of the Prairies ($1.4 \text{ m}^3/\text{s}$) and a relatively long travel time of 15.6 days. The June 19 2002 period allowed testing of the model under similar hydrologic and climatic conditions as the June 5 2002 initial model development and calibration period. Discharge during the July 24 2002 period was also low ($1.4 \text{ m}^3/\text{s}$) and represented the second longest travel time (17.8 days) from Lake of the Prairies to Brandon, in part due to the low observed incremental inflows and tributary inputs. The July 24 2002 time period was added to test the robustness of the initial June 5 2002 model to a change in time period from late spring to mid-summer. In contrast, the June 13 2001 period was chosen to represent higher discharge and a relatively short time of travel. During the June 13 2001 period, double the outflow occurred from Lake of the Prairies ($2.8 \text{ m}^3/\text{s}$) with a travel time of only 12.7 days (Table 3). Comparison of model results from these different discharge scenarios and time periods allowed testing the robustness of the model over a range of conditions.

6.1 June 5, 2002 Model Development and Calibration

An increase in observed TP concentrations was measured between Lake of the Prairies (river km 0) and just upstream of the confluence with the Little Saskatchewan River (river km 429.9) (Figure 10). Total P concentrations increased from 0.061 mg/L at Lake of the Prairies to 0.223 mg/L just upstream of the confluence with the Little Saskatchewan River. Total P concentrations then decreased considerably downstream of the confluence with the Little Saskatchewan River suggesting that dilution influenced phosphorus concentrations at this station. While the overall trend was an increase in TP concentration towards the downstream end of the study reach, downward fluctuations between stations were as much as 0.042 mg/L . Inorganic phosphorus concentrations were closely correlated with TP concentrations

(Spearman's Rho 0.86, $P < 0.0001$) and also increased between Lake of the Prairies and the confluence with the Little Saskatchewan River (Figure 11). As with TP, inorgP concentrations decreased considerably downstream of the confluence with the Little Saskatchewan River. Modelled TP and inorgP concentrations closely matched observed concentrations (Table 6 Initial Model). Similar to observed concentrations, the water quality model predicted a gradual increase towards the downstream end of the study reach with a sharp decline after the confluence with the Little Saskatchewan River. Both TP and inorgP were modelled with high precision and accuracy. In contrast, TOP concentrations fluctuated between 0.036 and 0.088 mg/L along the study reach and no clear longitudinal trends were evident (Figure 12). Therefore, modelled TOP concentrations remained relatively constant between 0.05 and 0.08 mg/L along the river and the relationship between modelled and observed concentrations was considerably weaker (Table 6 Initial Model) than for either total or inorganic phosphorus.

Concentrations of NH_3 and NO_2NO_3 were below detection limits for the entire sampling period during June 5 2002 (Figures 14 and 15). Even though modelled concentrations of NH_3 appeared to be similar to those observed in the Assiniboine River (Figure 14), assessment of model accuracy and precision was not possible. Although calculation of TON and TN concentrations were impacted by censored concentrations of NH_3 and NO_2NO_3 , both were modelled with some precision and high accuracy across the study reach (Figures 13 and 16, Table 6 Initial Model). Observed concentrations of TON and TN fluctuated considerably between stations but a general decline in both constituents was predicted by the model.

Observed chl *a* concentrations fluctuated by approximately 20 $\mu\text{g/L}$ across the study reach during the June 5 2002 modelling period. Chlorophyll *a* concentrations declined rapidly between Lake of the Prairies (river km 0) and the confluence with the Qu'Appelle River at St. Lazare (river km 121.8) from about 20 to 7 $\mu\text{g/L}$ (Figure 8). After considerable input from the Qu'Appelle River (45.9 $\mu\text{g/L}$), concentrations of algal biomass in the Assiniboine River remained relatively higher than those measured upstream (max 26.8 $\mu\text{g/L}$) with fluctuations as much as 10 $\mu\text{g/L}$ between stations located less than 4 km apart. Chlorophyll *a* concentrations appeared to decline downstream of Virden (river km 304.3) but remained higher than those observed just upstream of the confluence with the Qu'Appelle River (12 $\mu\text{g/L}$). Modelled chl *a* concentrations followed the general trend of the observed data and predicted the decline to St.

Lazare and the dramatic rise after the confluence with the Qu'Appelle River. Although the resulting water quality model predicted the overall longitudinal trend in chl *a* concentrations with considerable precision and high accuracy (Table 6 Initial Model), fluctuations between stations were generally not well modelled.

Dissolved oxygen concentrations fluctuated between 9.7 and 4.7 mg/L along the study reach during the June 5 2002 modelling period (Figure 7). At the PTH #21 bridge near Griswald (river km 373.3), DO concentrations dipped below the instantaneous surface water quality objective for cool water aquatic life (water temperature >5°C) of 5 mg/L but rose to well above the objective at the next station about 46 km downstream. Generally, observed DO concentrations were predicted with high accuracy and precision by the model (Table 6 Initial Model). However, the decline in DO concentration to below the instantaneous surface water quality objective at the PTH #21 bridge was not predicted.

6.2 June 5 2002 Model Testing and Calibration

Testing of the June 5 2002 initial model on the three independent sampling periods (June 19 2002, July 24 2002, and June 13 2001) indicated that conservative constituents such as conductivity were well predicted (Tables 7 through 9 Initial Model). Of the remaining constituents, only TP, inorgP, and TSS were well predicted across all three test periods. Model predictions of chl *a*, DO, and the various nitrogen fractions were considerably different than observed concentrations suggesting that rates, constants, and coefficients influencing these constituents varied across test sampling periods.

Total and inorganic phosphorus concentrations between Lake of the Prairies and the City of Brandon during the three test periods for the spring/early summer period followed the same increasing trend as observed during the initial June 5 2002 sampling period. Consequently, model calibration for the un-manipulated June 5 2002 model predicted both TP and inorgP with considerable precision although accuracy was occasional lacking (Tables 7 through 9 Initial Model). Although an overall increasing trend could still be observed, model precision was poorest during the June 19 2002 sampling period when TP appeared to fluctuate considerably between stations. Total OP concentrations were also predicted with high accuracy and precision during the July 24 2002 and June 13 2001 but not the June 19 2002 sampling period where TOP

concentrations were generally overestimated. Manipulation of rates of inorgP flux from the benthos generally improved model precision and accuracy for prediction of inorgP and TP (Tables 7 through 9 After Manipulation) suggesting that both are greatly influenced by external P sources. The rate of soluble OP hydrolysis was also adjusted for all three sampling periods to improve model calibration for total, organic, and inorganic phosphorus.

Nitrogen fractions were generally poorly modelled by the un-manipulated model for all three test periods (Tables 7 through 9 Initial Model). The predominance of NH_3 , NO_2NO_3 , and/or TON concentrations below laboratory detection limits throughout the test periods likely negatively impacted model calibration for N fractions. Assessment of model precision was also difficult when the range in concentrations of NH_3 , NO_2NO_3 , and/or TON was narrow (Hakanson *et al.* 2003). Manipulation of rates of NH_4 release from the benthos, nitrification, and soluble ON hydrolysis were attempted to improve calibration but no improvement in model precision or accuracy for the various N fractions was observed (Tables 7 through 9 After Manipulation). Despite the poor overall model performance for N indicated by model precision, model accuracy for TN was good throughout all sampling periods. While between-station fluctuations in N could not be predicted by the model, overall modelled TN concentrations were in the range of those observed in the Assiniboine River during the spring/early summer of 2001 and 2002.

Modelling of chl *a* concentrations during the three test periods for the spring/early summer was poor with no relationship detected between observed and predicted concentrations (Tables 7 through 9 Initial Model). Manipulating rates, constants, and coefficients in the water quality model improved chl *a* concentration prediction only slightly across the three test periods. Increasing algal settling velocity improved model precision and accuracy for chl *a* during the July 24 2002 period while increasing background light extinction improved model accuracy during the June 13 2001 period. In particular, chl *a* concentrations that fluctuated as much as 12.8 $\mu\text{g/L}$ within 10 km were poorly modelled by QUAL2K. Many of the rates, constants, and coefficients that impact algal biomass must be set for the entire model and cannot be reach specific. Therefore, variation in the processes that influence chl *a* concentrations over small spatial scales cannot be varied across the study reach. Clearly, chl *a* concentrations were poorly modelled during the spring/early summer period in the Assiniboine River with only the initial June 5 2002 sampling period modelled with high accuracy and precision.

Dissolved oxygen concentrations were poorly modelled with respect to accuracy and precision for three test periods during the initial spring/early summer modelling process (Tables 7 through 9 Initial Model). Modifications to reach-specific rates of SOD greatly improved model accuracy and precision for the June 19 2002 and July 24 2002 models (Tables 7 and 8 After Manipulation). Interestingly, manipulated SOD rates during the June 5 2002, June 19 2002, and July 24 2002 periods were positively correlated suggesting that patterns in SOD were similar across the study reach during these time periods (Spearman's $Rho > 0.55$, $P < 0.0001$). Despite considerable modification in SOD rates, no detectable relationship could be derived between modelled and observed DO concentrations for the June 13 2001 period even though model accuracy improved considerably (Table 9 After Manipulation). The weak relationship between modelled and observed concentrations may have been due to the narrow range in DO concentrations downstream of the Qu'Appelle River confluence. Overall, three of the four periods modelled during the spring/early summer sampling periods had similar rates of SOD suggesting that average rates could be used to develop a final model for the period.

6.3 Final Spring/Early Summer Model

Comparisons of calibrated models for each of the three test periods and the initial model for June 5 2002 suggested that while modifications to some rates, constants, and coefficients improved model calibration during the test periods, the June 5 2002 model provided the best overall model for the spring/early summer period. Only rates of SOD developed for the June 5 2002 model were modified to improve model accuracy and precision across the test periods. Sediment oxygen demand rates developed from three of the four periods (June 5 2002, June 19 2002, and July 24 2002) were averaged across each model reach to produce a model that was well calibrated for DO during three of the four sampling periods. The resulting final water quality model for the spring/early summer period predicted conductivity, TP, inorP, and TSS during all four of the sampling periods with high precision and considerable accuracy (Tables 6 through 9 Final Model). As discussed, modelling of TN and the various N fractions was difficult due to censored concentrations of NH_3 and NO_2NO_3 . However, the June 5 2002 model was accurate and precise for prediction of both TN and TON concentrations suggesting that future assessments of the Assiniboine River during the spring/early summer could be done with the June 5 2002 model. Similarly, chl *a* concentrations were only well modelled during the June 5

2002 sampling period providing increased support for the use of the June 5 2002 model for assessments of water quality in the Assiniboine River during the spring/early summer period.

The final water quality model for the spring/early summer period (June 5 2002) was then tested on a new sampling period (May 9 2002) that was not used to develop the final model (Table 10). Similar to sampling periods used to develop the final spring/early summer model, discharge from Lake of the Prairies during the May 9 2002 sampling period was among the lowest ($1.4 \text{ m}^3/\text{s}$) and travel times were the fourth longest during the study (16.4 days) (Table 3). However, since sampling periods used to develop the final model were from June and July, use of the May period tested the robustness of the model to a change in time period.

During the May 9 2002 period, on average, 86 % of the observed concentrations for conductivity, DO, chl *a*, TP, inorgP, TN, TON, and TSS fell within the prediction intervals (Figures 18 to 25). Prediction intervals were not developed for the remaining constituents since relationships between observed and predicted concentrations were not detected statistically in the final model (June 5 2002). All of the observed concentrations for TN and TON fell within the prediction intervals suggesting that the final model was able to predict these two constituents successfully. Yet given the wide range of predicted concentrations (Figures 23 and 24), it was not unexpected that the observed concentrations would fall within the predicted. The usefulness of model predictions that range as much as 1.3 mg/L is also limited. For the remaining constituents (conductivity, DO, chl *a*, TP, inorgP, and TSS) more than about 70 % of the observations fell within the predicted range despite more narrow prediction intervals. The ability of the final spring/early summer model to predict more than 86 % of the observed conductivity, DO, chl *a*, TP, inorgP, TN, TON, and TSS concentrations during the May 9 2002 sampling period suggested that the model was robust enough to compensate for fluctuation in time period within the spring/summer season.

7.0 Open Water Model Two – July/August

An initial open water model for July/August was developed and calibrated for the time period beginning July 25, 2001. Discharge from Lake of the Prairies was moderate ($2.8 \text{ m}^3/\text{s}$) during a study period (2001 to 2003) dominated by relatively low discharge (Table 3). Discharges contributed by the three tributaries were all above the medians for the study period,

with discharge from the Little Saskatchewan River at the second highest level observed during the study. Incremental inflows during the period ($8.8 \text{ m}^3/\text{s}$) were also considerably higher than the median for the study period ($2.3 \text{ m}^3/\text{s}$). As a result, discharge at Brandon was the sixth highest observed during the study period ($29.2 \text{ m}^3/\text{s}$). Overall time of travel from Lake of the Prairies to Brandon was the fourteenth fastest for the study period at 12.9 days (Table 3).

Four different time periods (August 8 2001, July 24 2002, August 7 2002, and August 21 2002) were used to test the initial model developed for the July 25, 2001 period. Discharges from Lake of the Prairies, the Qu'Appelle River, and Birdtail Creek were similar during the August 8 2001 and July 25 2001 sampling periods. However, incremental inflows and discharge in the Little Saskatchewan River were higher in July than in August 2001. The three remaining sampling periods selected from 2002 provided a test of the July 25 2001 model for a different year and under different discharge conditions. Discharge from Lake of the Prairies during July 24 2002 ($1.4 \text{ m}^3/\text{s}$) was about half that during the initial July 25 2001 period ($2.8 \text{ m}^3/\text{s}$). Travel times to Brandon during July 24 2002 were the second slowest observed during the study (17.8 days) due not only to low discharge from Lake of the Prairies but also from the three tributaries (Table 3). In contrast, discharges from Lake of the Prairies during the August 7 and 21 2002 sampling periods ($4.2 \text{ m}^3/\text{s}$) were 1.5 times higher than those observed during the initial July 25 2001 period. Travel times during August 2002 (12.8 and 13.9 days) were quite similar to those observed during the initial period (12.9 days). The four test periods provided both a wide range of discharge conditions and a multi-year comparison for testing of the initial model for July 25 2001.

7.1 July 25, 2001 Model Development and Calibration

Although both total N and P concentrations in the Assiniboine River were well predicted by the initial model for July 25 2001, various N and P fractions were poorly predicted (Table 11 Initial Model). Total N concentrations decreased gradually between Lake of the Prairies (river km 0) and the City of Brandon (river km 435), while TP concentrations increased along the same river reach (Figures 29 and 32). In contrast, NH_3 and NO_2NO_3 concentrations fluctuated as much as 0.15 mg/L between stations and were poorly predicted by the model (Figures 33 and 34). Only TON concentrations, which followed the same trend as TN, were predicted with high

precision and considerable accuracy by the model (Figure 35). While inorgP concentrations followed the same trend as TP and were well predicted by the model, organic P concentrations fluctuated as much as 0.9 mg/L between stations and were poorly predicted (Figures 30 and 31).

Difficulty in modelling fractions of N and P may be due in part to the method used by the model to determine organic N and P. QUAL2K calculates total organic fractions as the sum of the soluble concentrations specified by the user and the fraction of N or P contained in detritus and algae as determined by the user specified stoichiometric ratios. In some cases, model calculated algal and detrital N or P was greater than either the TON (TKN minus NH_3) or TOP (TP minus inorgP) concentrations measured in the river. Thus overestimated algal and detrital N and P concentrations suggested that soluble concentrations were zero and stoichiometric ratios were overestimated. South and Whittick (1987) also noted that stoichiometric ratios were not well defined and may vary in time and space. Despite the potential for variable stoichiometric ratios in nature, the QUAL2K model requires the use of constant ratios. Consequently, summer detrital fractions were considered zero and not modelled during this summer simulation. Ignoring the detrital fraction was not considered a loss to the Assiniboine River water quality model because detritus concentrations were estimated rather than measured and the previous version, QUAL2E, did not include modelling of detrital fractions. Removal of detrital N and P eliminated some of the overestimation of TON and TOP by the model. Model assumptions and a lack of measurement of concentrations of detritus and soluble N and P may have impacted predictions of total organic N and P fractions in summer.

Observed chl *a* concentrations decreased downstream of Lake of the Prairies due to increased light limitation, but then increased to about 11 $\mu\text{g/L}$ after the confluence with the Qu'Appelle River (river km 122.6) (Figure 27). Chlorophyll *a* concentrations then remained fairly constant until Griswald (river km 373.3) before decreasing sharply near Brandon (river km 435). Modelled concentrations did not follow the trend in the observed data. Although background light extinction was set and fixed to a single value for the entire model, fluctuations in light penetration were simulated by the model by changes in inorganic suspended sediments or detritus concentrations. The drop in chl *a* concentration downstream of Lake of the Prairies was reproduced in the model when light extinction due to suspended sediments and detritus was increased. However, under this increased light extinction, chl *a* concentrations also decreased to

less 1 $\mu\text{g/L}$ downstream of the Qu'Appelle River, a trend that was not observed in the river and resulted in excessive concentrations of DIN. Clearly, two different light extinction coefficients were required during this period, with the Qu'Appelle River confluence forming the transition between the two coefficients. However, with the QUAL2K model limited to a single light extinction coefficient, calibration for the river reach between Lake of the Prairies and the Qu'Appelle River was sacrificed in favour of calibration in the longer downstream reach. The resulting relationship between observed and modelled chl *a* concentrations, although precise, was negative (Table 11 Initial Model) suggesting that the model was unable to predict chl *a* concentrations in the Assiniboine River during this period.

Dissolved oxygen concentrations during the July 25 2001 sampling period were relatively low as compared to others observed during the study. Dissolved oxygen concentrations at Lake of the Prairies during this period were the fourth lowest observed throughout the study at this site (6.1 mg/L) and concentrations decreased to less than 3 mg/L near Miniota (river km 218.1) (Figure 26). Concentrations then increased to over 7 mg/L near the City of Brandon (river km 435). Manipulation of SOD rates resulted in excellent correlation between observed and predicted DO concentrations (Table 11 Initial Model). However, rates of SOD were quite high, averaging 13.5 gO/m²/d (range 7 to 20 gO/m²/d). Calibrated rates for this study were well above measured rates from a study on the lower reaches of the Assiniboine River in August 2002 (range 0.5 to 2.8 gO/m²/d) (North *et al.* 2002). However, SOD rates measured by North *et al.* (2002) were not tested in a calibrated model so it is unknown if the measured rates reflected modelled conditions observed in the river. In addition, calibrated SOD rates during the July 25 2001 sampling period, although higher than those measured by North *et al.* (2002), were well below maximum rates in the literature (40 gO/m²/d in Bowie *et al.* 1987).

7.2 July 25, 2001 Model Testing and Calibration

Testing of the July 25, 2001 initial model on the four independent sampling periods (August 8 2001, July 24 2002, August 7 2002, and August 21 2002) indicated that conservative constituents such as conductivity were well predicted (Tables 12 through 15 Initial Model). Of the four test periods, the un-manipulated August 7 2002 model predicted the most constituents (conductivity, TON, NH₃, TN, inorgP, TP, TSS, and chl *a*) with a relatively high level of

precision and some accuracy (Table 14 Initial Model). The August 8 2001 and August 21 2002 un-manipulated models performed the poorest with only four variables predicted with high precision and some accuracy (Tables 12 and 15 Initial Model). Rates, constants, and coefficients were therefore modified to improve model precision and accuracy.

Total and inorganic phosphorus concentrations during three (August 8 2001, July 24 2002, August 7 2002) of the four test periods followed the same increasing trend between Lake of the Prairies and Brandon as observed during the initial July 25 2001 sampling period. Consequently, the un-manipulated July 25 2001 model predicted TP and inorgP with considerable precision, although accuracy was often lacking (Tables 12 through 14 Initial Model). Model manipulation of benthic flux of inorgP generally improved model accuracy (Tables 12 through 14 After Manipulation). However, during the fourth test period (August 21 2002), TP and inorgP concentrations declined downstream of Lake of the Prairies to the confluence with the Qu'Appelle River (river km 121.8). Phosphorus concentrations then fluctuated with no apparent pattern across the rest of study reach (Figures 37, 38, and 38). Algal growth rates, the P half-saturation constant, and other rates impacting algal growth were modified in an attempt to decrease TP and inorgP concentrations up to the confluence with the Qu'Appelle River. However, modelled concentrations remained much larger than observed between Lake of the Prairies and the confluence with the Qu'Appelle River and did not follow the fluctuations observed in the downstream portion of the study reach.

As with the initial July 25 2001 sampling period, stoichiometric ratios impacted model calibration during the August 21 2002 sampling period. The model overestimated TP and TOP concentrations (Figures 37 and 39) during this sampling period due to the large influx of algae and associated P (Figure 40) into the Assiniboine from the Qu'Appelle River. Model calculation of TP based on the sum of inorgP and the fraction of P in algae greatly exceeded measured TP concentrations. In fact at some stations, based on the stoichiometric ratios used by the model, the estimated P concentration in algae alone exceeded total P concentrations measured analytically. The P content of algal cells is known to vary due to luxury consumption and P deficiency (South and Whittick 1987). Based on TP, inorgP, and chl *a* concentrations in the Qu'Appelle River (and assuming soluble organic P concentrations were below detection), the ratio of P to chl *a* was 0.22 as compared to the 1.4 set as model input. Comparison of P to chl *a*

ratios in the Assiniboine River between Lake of the Prairies and Brandon indicated that ratios were at least 1.4 up to the confluence with the Qu'Appelle River, and then fluctuated to as low as 0.4 downstream of the confluence. Manipulation of model stoichiometric ratios from 1.4 to about 0.4 slightly improved calibration of TP and TOP (Table 15 After Manipulation). However, an inability to set reach variable ratios negatively impacted model calibration during the August 21 2002 sampling period.

In contrast to P, TN and the various N fractions were poorly modelled across all four test periods (Tables 12 through 15 Initial) and did not display strong increasing or decreasing trends across the study reach. Poor model calibration for nitrogen fractions may be in part due to observed TKN and/or NO_2NO_3 concentrations below detection limits during the July 24 2002 and August 7 2002 modelling periods. Manipulation of rates, constants, and coefficients did not improve model precision and accuracy for N fractions during the July 24 2002 and August 7 2002 modelling periods (Tables 13 and 14 After Manipulation). None of the N fractions were modelled well for either the initial or manipulated model for August 8 2001 (Table 12 Initial Model and After Manipulation). While NH_3 concentrations were modelled with some precision during the August 21 2002 period, accuracy was limited. Difficulties in model calibration for TN, TON, and NO_2NO_3 , as with phosphorus, may have been impacted by inappropriate, constant stoichiometric ratios. Ratios of N to chl *a* ranged from greater than 8.5 to less than 2 along the study reach suggesting that reach variable inputs of stoichiometric ratios could have improved model calibration during the August 21 2002 sampling period. In general, manipulation of model rates such as nitrification, denitrification, organic N mineralization, and influx of NH_4 from the benthos did not greatly improve model calibration for TN or the various N fractions. Lack of detectable trends in N concentrations across the river probably impacted calibration.

Chlorophyll *a* concentrations were also poorly modelled during the four test periods with respect to precision since the models were generally unable to predict the fluctuations that occurred in concentration (Tables 12 through 15 Initial Model). However, the percent difference between observed and modelled chl *a* concentrations was generally small suggesting that while the model was unable to predict fluctuations between sites, modelled concentrations along the river study reach were within the expected range. Given that mean chl *a* concentrations varied from 5.6 to 65.9 $\mu\text{g/L}$ between sampling periods, the ability of the model to predict the mean

range of chl *a* concentrations in any one period was significant. Only the August 7 2002 model suffered from relatively poor model accuracy (62 %) (Figure 41). Manipulation improved model accuracy for chl *a* (36 %) although precision declined considerably due in part to the large variability in between chl *a* concentrations between stations.

The two sampling periods during July and August 2001 exhibited similar trends in chl *a* concentrations. During the July 25 2001 and August 8 2001 sampling periods, chl *a* concentrations decreased fairly continuously downstream of Lake of the Prairies to the confluence with the Qu'Appelle River (river km 121.8) (Figures 27 and 42). Downstream of the confluence with the Qu'Appelle River, higher chl *a* concentrations in the Qu'Appelle River supplemented concentrations in the Assiniboine River. Concentrations of chl *a* then remained relatively constant (July 25 2001) or declined (August 8 2001) downstream towards Brandon. Despite a fairly predictable overall trend for these two periods, modelled concentrations were considerably different from observed (Tables 11 and 12 Initial Model). Reasons for these differences were not fully known. Throughout the study, turbidity was significantly lower on average at the outlet of Lake of the Prairies as compared to the rest of the Assiniboine River stations ($P < 0.0001$). The difference in turbidity between the outlet of Lake of the Prairies and the next station downstream at Russell (river km 46.1) was more than 25 mg/L during July and August 2001, a considerably larger difference than observed for the three periods modelled during 2002. Incremental inflows between Lake of the Prairies and Russell were from four to eight times higher during the 2001 compared to the 2002 sampling periods. Highly turbid incremental inflows between Lake of the Prairies and Russell likely reduced light penetration in these first few reaches of the study area during 2001. The decline in chl *a* concentrations downstream of Lake of the Prairies was consistent with light limitation because both N and P concentrations were not limiting during the two sampling periods. However, background light extinction must be set for the entire model in QUAL2K, and as with the stoichiometric ratio, cannot be adjusted for each reach throughout the model. Light extinction could be manipulated within the model by adjusting turbidity and inorganic suspended solids concentrations. However when manipulation reduced extinction rates sufficiently to quickly reduce chl *a* concentrations to expected values just downstream of Lake of the Prairies, chl *a* concentrations downstream of the Qu'Appelle River also declined quickly, a trend not observed in these data. Predicting the

observed decline in chl *a* concentrations downstream of Lake of the Prairies during July and August 2001 was only possible when calibration for downstream stations was sacrificed.

Although DO concentrations were poorly modelled with respect to accuracy and precision for each of the four test periods (Tables 12 through 15 Initial Model), modifications to reach-specific rates of SOD greatly improved model accuracy and precision (Tables 12 through 15 After Manipulation). In all four test periods, the maximum and average rates of SOD were low as compared to the initial July 25 2001 sampling period. Manipulated rates of SOD during the four test periods were not correlated with those developed for the July 25 2001 model suggesting that patterns in SOD differed between reaches in different months and years. Of the manipulated rates, only those for the two early August periods from 2001 and 2002 were positively correlated (Spearman's $\rho = 0.58$, $P < 0.0001$). Although manipulation of SOD rates greatly improved model calibration for DO, use of month- and year-specific, reach-variable rates of SOD made it difficult to develop a single water quality model that could be applied during the July/August period.

7.3 Final July/August Water Quality Model

Comparisons between calibrated models for each of the four test periods and the initial model for July 25 2001 suggested that the rates, constants, and coefficients derived for the July 24 2002 model, when applied to the remaining three test periods and the initial period, provided the best overall accuracy and precision for the most constituents (Tables 11 through 15. Final Model). With the rates, constants, and coefficients for the July 24 2002 model, all periods except August 21 2002 were well modelled with respect to both accuracy and precision for TP and inorgP concentrations. Total suspended solid concentrations were also well modelled with high precision and considerable accuracy across three of the five sampling periods. As with the individually calibrated models, nitrogen fractions were generally poorly modelled but TN concentrations were accurately and precisely modelled for two of the five periods. Chlorophyll *a* concentrations were also fairly well modelled during three of the five periods although model accuracy was occasionally lacking. While prediction of specific N fractions was limited during the July/August period, modelled TN, TP, inorgP, and chl *a* concentrations were similar to those observed within the Assiniboine River.

Use of a single set of SOD rate coefficients for all five models resulted in weak relationships between observed and predicted DO concentrations. Accurate and precise final models were developed for dissolved oxygen only during the July 24 2002 and August 7 2002 sampling periods. Consequently, calibrated SOD rates for the July 24 2002 sampling period were replaced by mean SOD rates calculated from all five sampling periods. Model calibration for DO then improved overall with lower percent mean error between observed and predicted concentrations (Tables 11 through 15 Final Model).

The final water quality model for the summer period was then tested on two new sampling periods (July 16 and July 29 2003) that were not used to develop the final model. As indicated by the faster travel times, headwater and tributary discharges were generally higher during the July 16 and July 29 2003 sampling periods compared to those used to develop the final summer model (Table 3). Outflows from Lake of the Prairies were as much as six times higher than those observed during the development of the final model. In addition, discharge in the Qu'Appelle River was among the highest observed during the study. However, incremental inflows were considerably lower during the July 2003 period (0 to 1.4 m³/s) as compared to those during the sampling periods used to develop the final model (2.2 to 8.8 m³/s). Low incremental inflows were likely due to relatively low precipitation during July 2003. Testing the final summer model on the July 2003 sampling periods provided a test of different headwater and tributary discharges, variation in incremental inflows, and a change in year from 2001 and 2002 to 2003.

During the July 16 2003 period, on average, 68 % of the observed DO, chl *a*, conductivity, TP, inorgP, TN, and TON concentrations fell within the prediction intervals (Figures 43 through 49). Model prediction was poorest for inorgP and conductivity with approximately 40 to 46 % of the observed concentrations falling within the predicted range (Figures 45 and 47). However, prediction intervals were relatively narrow for conductivity (Figure 45). Dissolved oxygen was well modelled with 64 % of the observed concentrations falling within a relatively narrow range predicted by the model (Figure 43). Although a high percentage of the observed concentrations of chl *a*, TP, TN, and TON were within the predicted intervals, the relatively wide intervals limited this model's usefulness for future predictions. Similarly, during the July 29 2003 period, on average 78 % of the observed DO, chl *a*,

conductivity, TP, inorgP, TN, and TON concentrations fell within the prediction intervals (Figures 50 through 56). As with the July 16 2003 period, model prediction was poorest for inorgP with only 40 % of the observed concentrations falling within the relatively wide prediction intervals (Figure 54). However, in contrast to the July 16 2003 sampling period, the model predicted 100 % of the conductivity concentrations within relatively narrow intervals (Figure 52). Dissolved oxygen was also well modelled with 86 % of the observed concentrations falling within the range predicted by the model (Figure 51). Wide prediction intervals for chl *a*, TP, TN, and TON concentrations resulted in most of the observed concentrations falling within the narrow predicted range. The ability of the model to predict, on average, between 68 and 78 % of the observed concentrations suggested that the summer water quality model provided an excellent model for chl *a*, DO, and nutrients in the Assiniboine River during this time period. However, as with the spring/early summer model, the wide prediction intervals limit the scale to which the model could be applied.

8.0 Open Water Model Three – September/October

An initial open water model for September/October was developed and calibrated for the time period beginning September 19 2001. Discharge from Lake of the Prairies was moderate ($2.8 \text{ m}^3/\text{s}$) when compared to the overall study period median (2001 to 2003) (Table 3) but discharges contributed by the three tributaries were below the medians for the study period (Table 3). In contrast, incremental inflows during the September 19 2001 period were higher than the median for the study period (Table 3). As a result, both discharge at Brandon and overall travel time (14.8 days) from Lake of the Prairies to Brandon were similar to the medians for the overall study period (Table 3).

Four different periods were used to test the initial model developed for the September 19 2001 period (September 4 2001, October 10 2001, September 18 2002, and October 15 2002). Headwater discharge during the September 4 2001 and September 18 2002 sampling periods was the same as that during the initial September 19 2001 period with overall travel times to Brandon being relatively similar at 15.3 and 15.4 days. In contrast, headwater discharge from Lake of the Prairies during the October 10 2001 and October 15 2002 sampling periods (5 and $5.7 \text{ m}^3/\text{s}$) was approximately double that during the initial period ($2.8 \text{ m}^3/\text{s}$). Discharge in the Qu'Appelle

River during the five sampling periods ranged from less than 1 m³/s during the initial September 19 2001 test period to more than 3 m³/s during the October 10 2001 sampling period. Incremental inflows ranged from some of the largest observed (7.1 m³/s September 19 2001) to those well below the median for the study period (September 18, 2002, 0.8 m³/s and October 15, 2002, 1.3 m³/s). Discharges from Birdtail Creek and the Little Saskatchewan River were moderate to low during all five sampling periods (Table 3). The four sampling periods selected for testing during September and October 2001 and 2002 provided a wide range of discharge conditions and a multi-year comparison of rates and constants for testing of the initial model for the September 19 2001 sampling period.

8.1 September 19 2001 Model Development and Calibration

Comparisons between modelled and observed conservative constituents such as conductivity suggested basic model performance for the September 19 2001 sampling period (independent of rates, constants, and coefficients) was good. There was a strong relationship between observed and predicted conductivity values and a relatively low mean percent error (Table 16 Initial Model). Although the model predicted the observed increase in conductivity downstream of the Qu'Appelle River, it was unable to predict the magnitude of the increase.

The initial model developed for the September 19 2001 sampling period predicted all constituents except TON with high precision and considerable accuracy suggesting that this period provided an excellent initial model for the fall season (Table 16 Initial Model). The high accuracy and precision of the model could be because the observed concentrations of most constituents followed distinct trends and did not fluctuate widely between stations as was observed during other open water seasons (Figures 57 through 67).

Development of a well calibrated model for the September 19 2001 sampling period included typical modifications of rates, constants, and coefficients but also required considerable modification of the Qu'Appelle River tributary inputs. Initial modelling attempts indicated that chl *a* concentrations measured in the Qu'Appelle River were not high enough to predict the more than four fold increase in the Assiniboine River downstream of the confluence during the September 19 2001 sampling period (Figure 58). However, samples collected in July 2003 demonstrated that chl *a* concentrations in the Qu'Appelle River could fluctuate as much as 175

% over a relatively short time period of nine days. Consequently, chl *a* concentrations from the Qu'Appelle River point source inputs were manipulated to improve model accuracy and precision for chl *a* concentrations in the Assiniboine River during this time period.

8.2 September 19 2001 Model Testing and Calibration

Initial testing of the September 19 2001 model on four independent sampling periods (September 4 2001, October 10 2001, September 18 2002, and October 15 2002) indicated that conservative constituents such as conductivity were well predicted (Tables 17 through 20 Initial Model). Of the four test periods, the un-manipulated September 4 2001 model predicted the highest number of constituents (conductivity, TON, NH₃, TN, inorgP, TP, and chl *a*) with a relatively high level of precision and considerable accuracy (Table 17 Initial Model). Only DO, NO₂NO₃, TOP, and TSS were poorly modelled by the un-manipulated model (Table 17 Initial Model). Given that trends in constituents (Figures 68 to 78) and discharge conditions were similar between the initial September 19 2001 period and the September 4 2001 period, it was not surprising that the initial model would predict constituents well for both periods. Both the un-manipulated October 10 2001 and October 15 2002 models predicted about half of the constituents with high precision and some accuracy (Tables 18 and 20 Initial Model). Of the four test models, the un-manipulated September 18 2002 model performed the poorest with only four variables predicted with high precision and some accuracy (conductivity, inorgP, TP, TSS) (Table 19 Initial Model). Modifications to rates, constants, and coefficients were attempted during calibration to improve model precision and accuracy across all four sampling periods.

Model accuracy and precision were improved for all four test periods during the fall season after manipulation of model rates, constants, coefficients, and inputs (Tables 17 to 20 After Manipulation). Rates of SOD were modified considerably for all four test periods while rates of algal death were reduced to either 0.1/d or 0.05/d from the 0.15/d used in the September 19 2001 model. Algal settling was reduced to 0.001/d from 0.05/d in the October 10 2001 and September 18 2002 models. Supplemental inorgP flux from the benthos was also removed from all but the September 4 2001 model. Light extinction was decreased from 1 to 3/m in the October 10 2001 model and for the September 18 2002 model, ON hydrolysis was changed from 0.001 to 0.5/d. In addition, for all except the September 18 2002 model, manipulations to

incremental nutrient and detrital inputs improved model calibration. Incremental inflows varied throughout the testing periods with some characterized by large discharge ($4.5 \text{ m}^3/\text{s}$) while others were zero (Table 3). Since constituent concentrations for incremental inputs were estimated based on river rather than measured concentrations, manipulation of incremental inflow chemistry was appropriate to improve model calibration. However, manipulated incremental inflow chemistry provided some indication of the water chemistry of runoff to the Assiniboine River.

Despite considerable manipulation of rates, constants, and coefficients for the September 18 2002 sampling period, the model was unable to accurately and precisely predict many of the constituents (Table 19 After Manipulation). In particular, as with the late July and early August 2001 sampling periods, chl *a* concentrations decreased considerably (from $70 \text{ }\mu\text{g/L}$ to $17.3 \text{ }\mu\text{g/L}$) between the outlet of Lake of the Prairies and Russell (river km 46.1). Inorganic P and TP also declined considerably in the same 46 km reach. The water quality model was unable to predict these large decreases in chl *a* and phosphorus concentrations without considerable model manipulation that resulted in poor downstream model calibration. Therefore, model inputs of chl *a* and inorgP from the headwaters were reduced during the September 18 2002 sampling period until model calibration improved.

Two explanations exist for the discrepancy between measured concentrations at the outlet of Lake of the Prairies and concentrations predicted by the model during the September 18 2002 sampling period. First, large daily fluctuations in constituent concentrations observed at the outlet of Lake of the Prairies suggested that inputs to the Assiniboine River could have varied considerably over the 9 to 20 days required for water to travel from Lake of the Prairies to Brandon. Since only diurnal fluctuations in headwater chemistry can be modelled in QUAL2K, fluctuations in constituents over several days cannot be included. Second, water quality processes occurring in the 46 km reach between Lake of the Prairies and Russell likely differed from those along the rest of the study reach. For example, turbidity (and therefore light extinction), was considerably lower at the outlet of Lake of the Prairies as compared to the remaining stations on the Assiniboine River ($P < 0.0001$). Rates of light extinction attributed to ISS and detrital material may have varied considerably between the reach of the Assiniboine River near Lake of the Prairies and areas downstream of the Qu'Appelle River. Algal and

bacterial activity along with associated microbial processes such as nitrification may also have been enhanced in this reach due to relatively high nutrients and DO concentrations just downstream of the dam. Since many of the rates, constants, and coefficients must be set for the entire model, the reach variability that clearly existed in the Assiniboine River, particularly between Lake of the Prairies and Russell, could not be incorporated in the QUAL2K model.

8.3 Final September/October Water Quality Model

In contrast to other seasons, models developed during the September/October (fall) period required little manipulation to provide considerably precision and accuracy for all five sampling periods during 2001 and 2002. Inter-comparisons of the five calibrated models (four test and one initial) suggested that the model developed for the September 4 2001 sampling period provided the best overall model accuracy and precision for the most constituents across all five sampling periods (Tables 16 through 20 Final Model). When the rates, constants, and coefficients developed for the September 4 2001 model were applied to all five sampling periods, all except October 15 2002 were well modelled for TP and inorgP concentrations with respect to precision. As with the individually calibrated models, TON concentrations were generally poorly modelled but TN concentrations were accurately and precisely modelled for four of the five periods. Ammonia and NO_2NO_3 concentrations were precisely modelled during three of the five periods. Chlorophyll *a* concentrations were also modelled with high precision and accuracy during three of the five periods. With the exception of the September 18 2002 sampling period, which was poorly modelled even after considerable manipulation, each of the fall sampling periods was generally modelled with high precision and accuracy.

Rates of SOD developed for the September 4 2001 sampling period resulted in poor calibration between observed and predicted DO concentrations across all but the September 4 2001 sampling period. Various combinations of reach specific rates of SOD were modelled for each sampling period. From this process it was determined that a mean of SOD rates derived from both the September 19 2001 and September 18 2002 sampling periods provided the best overall combination of accuracy and precision across all periods.

The model development and calibration process for the fall season indicated that future assessments of the upper Assiniboine River during this period can be conducted with confidence.

While the September 19 2001 and September 4 2001 periods were modelled with the highest accuracy and precision, other periods with different headwater and tributary flows and chemistry (*i.e.*, October 10 2001 and October 15 2002 periods) were also modelled with some precision and accuracy for key constituents such as TN, TP, and chl *a* concentrations (Tables 16 to 20 Final Model). Future scenarios on the upper Assiniboine River should be modelled with the September 4 2001 final model since it provided the best overall model of observed conditions under different hydraulic conditions and varied water chemistry from headwater and tributary inflows.

The final water quality model for the fall period was then tested on a new sampling period, September 4 2002, which was not used to develop the model. It was not possible to find a test period that differed dramatically from those used to develop the model because sampling periods covering two years with a wide range of headwater and tributary discharges were used to develop the final fall water quality model. The September 4 2002 sampling period had a similar travel time (14.9 days), and similar headwater (2.8 m³/s) and tributary discharges (0.1 to 3.8 m³/s) to other periods used from September and October of 2001 and 2002. However, given that the September 4 2002 sampling period was not used to develop the fall water quality model, comparing model results with the observed concentrations from this period provided an additional independent test of the final model.

During the September 4 2002 period, on average, 66 % of the observed DO, chl *a*, conductivity, TP, inorgP, TN, NH₃, NO₂NO₃, and TON concentrations fell within the prediction intervals (Figures 79 through 87). Model prediction was poorest for chl *a* and conductivity with less than 50 % of the observed concentrations falling within the predicted range (Figures 80 and 81). Dissolved oxygen was well modelled with 77 % of the observed concentrations falling within the range predicted by the model (Figure 79). As well, more than 64 % of the observed concentrations for all the N and P fractions were within the range predicted by the model. The ability of the model to predict more than 64 % of the N and P fractions suggested the fall water quality model provided an excellent model for nutrient dynamics in the Assiniboine River during this time period.

9.0 Ice-covered Model One

An initial ice-covered model was developed and calibrated for the time period beginning January 28, 2002. Similar to the open water models developed for other seasons, discharge from Lake of the Prairies was moderate ($2.8 \text{ m}^3/\text{s}$) during a study period characterized by relatively low discharge. Discharges contributed by the three tributaries were just slightly below the study period median values while incremental inflows between Russell and Miniota were the second lowest observed throughout the study period (Table 3). Time of travel from Lake of the Prairies to Brandon was the seventh slowest for the study period at 15.9 days (Table 3).

Ice-cover was usually well established and continuous on the Assiniboine River from December to early April. Consequently, four different time periods starting December 17 2001, February 27 2002, April 3 2002, and December 17 2002 (Table 3) were used to test the initial ice-covered calibrated model. Discharge from Lake of the Prairies during three of the four sampling periods was $2.8 \text{ m}^3/\text{s}$ while discharge during April 3 2002 was $1.4 \text{ m}^3/\text{s}$. Tributary inflows during the four test periods included the lowest discharge from the Little Saskatchewan (December 2002, $0.5 \text{ m}^3/\text{s}$) and Qu'Appelle (April 3 2002, $0.6 \text{ m}^3/\text{s}$) rivers during the overall study period. However, the low discharge was balanced by relatively high inputs from the other tributaries during the same test periods. Overall, travel times for the four test periods were relatively slow. Travel times during December 2001 (15.5 days), February 2002 (16.0 days), April 3 2002 (15.0 days), December 2002 (14.1 days) were slower or just equal to the median for the study period (14.1 days). Although the four test periods did not represent a wide range in discharges from Lake of the Prairies and the three tributaries, comparison of model results tested the robustness of the calibrated model over the entire ice-covered season and across two sampling years.

9.1 January 28, 2002 Model Development and Calibration

Total nitrogen and NO_2NO_3 concentrations were modelled with high precision and accuracy while NH_3 and TON concentrations were poorly modelled during the initial January 2002 sampling period (Table 21 Initial Model). Observed TON concentrations fluctuated as much as 0.5 mg/L between stations along the 125 river km between Lake of the Prairies and the confluence with the Qu'Appelle River (Figure 97). Total organic N concentrations then

gradually increased between Miniota (river km 218.1) and Griswald (river km 373.3) before levelling off at Brandon (river km 435). Therefore, the initial water quality model was unable to predict either the wide fluctuations in TON concentrations or the gradual increase observed downstream of Miniota. Observed fluctuations in NH_3 concentrations between stations were also not well predicted by the initial model, in particular the large spike observed at Russell (river km 46.1) and the slight increases observed at Virden (river km 304.3) and Griswald (river km 373.3) (Figure 95). While fluctuations in NO_2NO_3 concentrations between stations were not well predicted, the overall increase in concentration between Lake of the Prairies and Brandon of approximately 4 mg/L was modelled with high precision (Figure 96). Except for a decrease in observed TN concentration just upstream of the confluence with the Qu'Appelle River, concentrations increased gradually between Lake of the Prairies and Brandon and were modelled with high precision and accuracy (Figure 94).

A gradual increase in observed TP concentrations was measured between Lake of the Prairies and Griswald (river km 373.3) during January 2002 (Figure 91). Total P concentrations increased from 0.057 mg/L at Lake of the Prairies to 0.087 mg/L at Griswald. Total P concentration decreased slightly downstream of the confluence with the Little Saskatchewan River (river km 435) suggesting that dilution influenced phosphorus concentrations at this station. Inorganic P concentrations were closely correlated with TP concentrations (0.98, $P < 0.0001$) and also gradually increased between Lake of the Prairies and Brandon (Figure 92). As with TP concentrations, inorgP concentrations decreased slightly downstream of the confluence with the Little Saskatchewan River (river km 435). Modelled TP and inorgP concentrations closely matched observed concentrations, mimicking the gradual increase towards the downstream end of the study reach and declining slightly after the confluence with the Little Saskatchewan River (Figure 91 and 92). Total OP concentrations generally declined between Lake of the Prairies and Brandon with fluctuations as much as 0.98 mg/L occurring between some stations (Figure 93). Although modelled TOP concentrations followed the general decline in the observed data, relatively large fluctuations between stations were not well modelled. Therefore, the relationship between modelled and observed TOP concentrations was considerably weaker than for either total or inorganic P during January 2002 (Table 21 Initial Model).

Observed chl *a* concentrations were low during the ice-covered January 2002 period and varied less than 2.5 µg/L across the study reach (Figure 89). Modelled chl *a* concentrations generally followed the observed concentrations at critical points such as downstream of the confluence with the Qu'Appelle River and demonstrated an overall increase in concentration between Lake of the Prairies and Brandon. However, the model was unable to predict relatively small changes in chl *a* concentrations such as between Griswald (river km 373.3) and Brandon (river km 435).

Dissolved oxygen concentrations fluctuated considerably between almost 10 mg/L at the well-aerated outlet of Lake of the Prairies to less than 3 mg/L at Griswald, just 65 km upstream of Brandon (Figure 88). Dissolved oxygen concentrations decreased more than 3 mg/L in the 46 river km between Lake of the Prairies and Russell and then fluctuated approximately 1.5 mg/L between stations just upstream of the confluence with the Qu'Appelle River. A missing sample near Miniota (river km 218.1) resulted in no DO measurements for approximately 183 river km between the Qu'Appelle River confluence and the next station at Virden (river km 304.3). At Virden, DO concentrations declined to less than 5 mg/L. Dissolved oxygen concentrations at the PTH 21 bridge near Griswald (river km 373.3) decreased below the instantaneous surface water quality objective for cool water aquatic life (water temperature >5°C) of 3 mg/L but increased to just above the objective at the next station 62 river km downstream near Brandon. It is not fully known why this increase in DO occurred under ice-covered conditions given limited potential re-aeration and algal production. Water quality samples collected for development of a water quality model for the Red River under ice-cover in North Dakota, showed variation in DO concentration over a 24 hour period could be up to approximately 1 mg/L (Wesolowski 1996). However, even if the concentration at Griswald was assumed to be a minimum value with an overall fluctuation as much as 1 mg/L, the maximum value of 3.7 mg/L would still be below the 7 day minimum surface water quality objective (Williamson 2002). Initial modelled DO concentrations followed the downward trend evident in the observed data and predicted the decline below the instantaneous surface water quality objective at the PTH 21 bridge near Griswald (Figure 88). Overall, the initial model predicted observed DO concentrations with high precision and accuracy (Table 21 Initial Model).

9.2 January 28, 2002 Model Testing and Calibration

Initial testing of the January 2002 model on the four independent sampling periods indicated that, with the exception of the April 3 2002 sampling period, conservative constituents such as conductivity were well predicted (Tables 22 through 25 Initial Model). During the April 3 2002 sampling period, the relationship between observed and predicted conductivity was not statistically significant, suggesting that the model did not reliably describe hydraulic conditions during the period. The April 3 2002 sampling period included ice and snow melt throughout the watershed with large incremental inflows occurring between gauging stations. As with other periods modelled throughout this study, chemistry data for incremental inflows were estimated from observed Assiniboine River data and assumed to be equivalent. While this method appeared effective during periods of low incremental inputs more accurate estimates of incremental inflow chemistry may be required to accurately and precisely model river water chemistry during times of high runoff.

Of the four test periods, the February 2002 model predicted the most constituents (conductivity, DO, NH_3 , NO_2NO_3 , inorgP, chl *a*) with a high level of precision and considerable accuracy (Table 22 Initial Model). The April 3 2002 un-manipulated model performed the poorest with only two variables predicted with high precision and accuracy (NO_2NO_3 , Chl *a*) followed by the December 2002 model that predicted only three constituents (conductivity, DO, NO_2NO_3) with high precision and accuracy (Tables 25 and 23 Initial Model, respectively). The December 2001 model performed slightly better with four constituents predicted with high accuracy and precision (Table 24 Initial Model). Rates, constants, and coefficients were modified during calibration to improve model precision and accuracy as well as to determine which processes impacted water chemistry in the Assiniboine River during the ice-covered season.

Manipulation of rates improved model accuracy and precision for several variables during December 2001 (Table 24 After Manipulation). In particular, both model accuracy and precision improved for inorgP, TP, and NH_3 concentrations. Model accuracy improved substantially for DO and chl *a* concentrations even though regression analyses indicated that the relationships between observed and predicted concentrations were not significant. Chlorophyll *a* concentrations, particularly at the downstream end of the reach, were relatively high compared to other ice-covered periods (Figure 99). Elevated chl *a* concentrations measured in samples at the

downstream end of the study reach may reflect samples collected from parcels of water that travelled through ice-free water during the journey from Lake of the Prairies to Brandon. Mean daily air temperatures at the nearby community of Shoal Lake were above zero degrees until late November and ice mainly formed in December. Therefore, conditions modelled during the December 2001 period (low light, temperature, and chl *a* concentration in outflow from Shellmouth) could not predict the high chl *a* concentrations observed at Brandon (Figure 99). Observed DO concentrations were well modelled between Lake of the Prairies and Virden (river km 304.3) and followed a general downstream decline (Figure 100). However, observed DO concentrations increased at Griswald (river km 373.3) and then again at Brandon (river km 435). Despite setting prescribed SOD rates to zero, predicted DO concentrations were not as high as those observed. Similar to conditions for chl *a*, open water conditions encountered by the parcel of water sampled at Griswald and Brandon could explain the lack of precision in prediction of DO concentrations at these stations.

Removal of the TP concentration measurement at Brandon (which was almost 3 times higher than any other observed during the sampling period) during the December 2002 model calibration, dramatically improved model precision and accuracy for TP concentrations that were relatively constant downstream of the Qu'Appelle River confluence (Figure 102). Chlorophyll *a* and TSS concentrations were also more than five times higher at Brandon compared to other stations. In contrast, inorgP concentrations at Brandon were more than five times lower than at the remaining stations across the river. An algal bloom in December 2002 near Brandon, as characterized by high chl *a*, TP, and TSS concentrations, may have depleted inorgP concentrations at this station. Modelling of remaining constituents improved little with model calibration.

Although the un-manipulated February 2002 model was precise and accurate for all but five constituents, model calibration improved accuracy (Table 22 Initial and After Manipulation). Except for TN, TON, and TOP, relationships between observed and predicted constituents in the manipulated model were statistically significant. In addition, removal of an outlier from the Binscarth station improved model calibration for TP and inorgP concentrations. The outlier at this station was likely caused by high concentrations of particulate, inorgP (which was not directly measured) indicated by elevated TSS, TP, and inorgP concentrations and

consistent chl *a*, TN, NO₂NO₃, NH₃, TON concentrations. Moderate contamination of the sample during collection may have artificially increased particulate, inorgP concentrations at this station. Similar to the January 2002 sampling period, downstream trends in observed data for the February 2002 period included declining DO concentrations, and increasing NO₂NO₃, TP, and inorgP concentrations (Figures 107, 110, 111, and 115). Of the four test models, the February 2002 period was most successfully modelled by the un-manipulated January 2002 initial model. Yet precision and accuracy for the February 2002 sampling period also improved most significantly in response to calibration.

As previously discussed, modelling the April 3 2002 period was difficult to model because constituents varied greatly between stations and trends in the observed data were generally not obvious. Only NO₂NO₃ and DO concentrations showed patterns consistent with other ice-covered sampling periods (e.g., Figure 121). Large incremental inflows (19.1 m³/s in total) resulting from ice and snow melt may have obscured trends in the observed data. Manipulation of rates, constants, and coefficients provided only minor improvements to model accuracy and precision. Clearly, steady state models such as QUAL2K were not able to model this late winter period with its wide fluctuations in chemistry and inflows.

9.3 Final Ice-Covered Model Development

Development of the ice-covered model for the Assiniboine River indicated sampling periods that occurred immediately after ice formation (December 2001 and 2002), or just prior to ice melt (April 3 2002), were characterized by highly variable constituent concentrations and were difficult to model. Only NO₂NO₃ concentrations followed a longitudinal, increasing trend during all five sampling periods (Figures 96, 101, 104, 115, and 121). Even DO concentrations, which gradually decreased between Lake of the Prairies and Brandon during four of the five ice-covered sampling periods, did not demonstrate this trend during December 2001 (Figure 100). It is possible that the lack of longitudinal trends in water chemistry was due to sampling various parcels of water between Lake of the Prairies and Brandon during the one- or two-day sampling periods during seasons of transition such as during ice melt and formation.

In contrast, the January and February 2002 sampling periods not only had similar headwater, tributary, and incremental discharges (Table 3), but also similar water chemistry with

respect to concentrations and longitudinal trends between Lake of the Prairies and Brandon. Except for DO, NO_2NO_3 , chl *a*, and alkalinity, there were no detectable differences between water chemistry at each station in January and February 2002 ($P < 0.05$). The final ice-covered water quality model was developed from a combination of the January and February 2002 models due to the similarity between the two sampling periods, both chemically and hydrologically, and because of the difficulties in modelling transition periods of ice formation and ice-melt during December 2001, December 2002, and April 3 2002. Comparisons between the two calibrated models indicated the February 2002 model generally provided the most accurate and precise model for both periods (Tables 21 and 22 Final Model). Consequently, the February 2002 model was adopted as the ice-covered model for the Assiniboine River between Lake of the Prairies and Brandon. The final model was considered well calibrated for conductivity, DO, NH_3 , NO_2NO_3 , inorgP, TP, chl *a*, and TSS based on the statistically significant relationships between observed and predicted concentrations.

The final water quality model for the ice-covered period was then tested on a new sampling period, January 2003 that was not used to develop the model. Discharges from the outlet of Lake of the Prairies during the January 2003 period were almost three times higher ($14.1 \text{ m}^3/\text{s}$) than the maximum observed throughout the periods used to develop the model (Table 3). Discharges from the Qu'Appelle River ($2.8 \text{ m}^3/\text{s}$), Birdtail Creek ($0.02 \text{ m}^3/\text{s}$), and the Little Saskatchewan River ($0.5 \text{ m}^3/\text{s}$) were in the range observed throughout the winter sampling periods during 2001 and 2002. Overall, travel time during January 2003 (11.2 days) was between three and about five days faster than those during the 2001 and 2002 sampling periods. Consequently, the January 2003 sampling period provided a good test of the final ice-covered water quality model across different years and discharge from the outlet of Lake of the Prairies.

During the January 2003 period, approximately 54 % of the observed concentrations of conductivity, DO, NH_3 , NO_2NO_3 , inorgP, TP, chl *a*, and TSS fell within the prediction intervals (Figures 124 through 131). All but one of the observed concentrations of DO, NH_3 , and NO_2NO_3 fell within the prediction intervals suggesting that the model was able to predict these three constituents. However, the range in prediction intervals for NH_3 and NO_2NO_3 concentrations was relatively large and it was not unexpected that the observed concentrations would fall within prediction limits. More than 50 % of the observed conductivity and inorgP

concentrations fell within the range predicted by the model. Finally, model predictions of chl *a*, TP, and TSS concentrations were poor with less than 23 % of the observed concentrations falling within the model prediction intervals. The January 2003 model provided a good test of the final water quality model (February 2002) with input from a different year and under higher discharge compared to the models used for development and calibration. The ability of the model to predict more than 50 % of the observed conductivity as well as DO, NH₃, NO₂NO₃, and inorgP concentrations suggested that the model is robust to both annual variation and fluctuations in headwater discharge.

10.0 Overall Modelling Results and Discussion

10.1 Rates, Constants, and Coefficients

Rates, constants, and coefficients used in the four final models are provided in Table 27. Many of the rates, constants, and coefficients used by QUAL2K must be set for the entire model and could not be varied across the 48 reaches. Of the non-reach variable rates, constants, and coefficients used in final QUAL2K models, 11 were varied between seasons (soluble ON hydrolysis, nitrification, denitrification, detrital dissolution, detrital and ISS settling velocity, rates of phytoplankton death and settling velocity, light extinction, algal preference for ammonia, and soluble OP dissolution). The 11 variable rates influenced concentrations of all three fractions of nitrogen (DON, NH₃, NO₂NO₃), DOP/inorgP, phytoplankton, and suspended solids/detritus.

With respect to nitrogen, rates of soluble ON hydrolysis, nitrification and denitrification were manipulated to directly impact NH₃, NO₂NO₃, and soluble ON concentrations. Organic N hydrolysis is the process where soluble ON is mineralized to form NH₃ with rates dependent on the presence and abundance of anaerobic bacteria and temperature. Thus manipulated rates of ON hydrolysis will impact concentrations of both DON and NH₃. During this study, temperature dependent rates of soluble ON hydrolysis were between 4 and 10 times higher in spring and summer compared to winter with the lowest rates occurring during fall. Nitrification is the process where NH₃ is oxidized to nitrite and then to nitrate thus the concentrations of all three would be impacted during manipulation. Nitrifying bacteria are aerobic therefore nitrification is an oxygen-limited process. Temperature dependent rates of nitrification were highest during

winter and then declined through spring and summer to reach a minimum in the fall. Kemp and Dodds (2002) suggested that rates of nitrification depend on available stream substrata. Perhaps winter conditions in the Assiniboine River were most favourable to the development of substrata for nitrifying bacteria thereby contributing to relatively high rates of nitrification. Finally, denitrification is the process where nitrate is converted to gaseous N_2 thereby representing a potential loss of N to the system. Denitrification occurs in both anaerobic and aerobic environments. Temperature dependent rates of denitrification were highest in summer and fall and lowest in spring with moderate rates in winter. As with rates of nitrification, denitrification depends in part on available substrata (Kemp and Dodds 2002) that may have affected the seasonal rates in the Assiniboine River. Rates of both nitrification and denitrification are also pH dependent such that rates decrease in more acidic waters. However, pH was well above 7.2 during the entire study suggesting that acidity did not influence rates of either nitrification or denitrification.

Rates of detrital dissolution as well as detrital and inorganic suspended solids (ISS) settling velocity were manipulated, not for improved calibration of detrital and TSS concentrations, but for the direct impact these variables had on other constituents and rates. For example, increased dissolution of detritus increases concentrations of both soluble organic N and P. Rates of ISS and detrital settling directly influence the concentrations of both constituents and thereby impact algal biomass through two light extinction coefficients - detritus and ISS light extinction ($1/m \cdot (mgD/L)$). Rates of detrital settling also impact the amount of particulate organic matter available for diagenesis and the resulting modelled-derived fluxes of inorgP and NH_4 from the benthos. Rates of ISS and detrital settling were highest in summer after considerable manipulation to influence phytoplankton biomass and benthic fluxes of inorgP and NH_4 . Rates of settling were low and fairly constant across the remaining three seasons.

Phytoplankton biomass (as chlorophyll *a*) was modelled in part through manipulation of rate of death, settling velocity, and background light extinction. The highest rate of death was observed in the summer, perhaps due to increased predation by zooplankton during the warmest months of the year or increased endogenous respiration (Thomann and Mueller 1987). Similarly, settling velocity was also highest in summer thereby removing large populations of algae from

the water column. However, rates of ISS and detrital settling velocity were also highest in the summer suggesting that the three rates of settling may be weakly correlated.

Of the rates impacting P concentrations, only soluble OP dissolution was modified across the seasons. Similar to soluble ON dissolution, the rate of soluble OP dissolution is the process where soluble OP is mineralized to form inorgP. Temperature dependent rates of soluble OP hydrolysis were highest in winter with lower rates in spring and summer and the minimum observed in fall.

In QUAL2K only three rates (SOD, NH_4 , and inorgP flux from the benthos) could be varied by the modeller across the 48 reaches. Consequently, rates of sediment nutrient fluxes and SOD in the four final models were varied across seasons and reaches. Rates of SOD, NH_4 , and inorgP benthic flux that were prescribed by the modeller supplement those rates that were estimated by the model. In addition to the modeller prescribed rates, QUAL2K estimated rates of SOD, NH_4 and inorgP flux based on rates of diagenesis, the downward flux of detritus (POM) and subsequent conversion into soluble reactive forms in the anaerobic sediments (Chapra and Pelletier 2003). Rates of diagenesis, while derived by the model, were impacted by several user input rates, constants, and coefficients such as detritus dissolution and settling velocity, phytoplankton settling velocity, and stoichiometric ratios.

Sediment oxygen demand (demand by benthic sediments and organisms for oxygen) can represent a large fraction of oxygen consumption in surface waters. Prescribed SOD rates used in models of downstream reaches of the Assiniboine River ranged between 0.07 and 2.76 $\text{g/m}^2/\text{d}$ and included measured rates as well as those calibrated by trial and error for the model (North *et al.* 2003). In an August study of the Red River near Moorhead, Minnesota, Wesolowski (1994) measured SOD rates of about 1.08 $\text{g/m}^2/\text{d}$. Sediment oxygen demand rates of 1.08 $\text{g/m}^2/\text{d}$ were used during the August study and in a subsequent ice-covered study (Wesolowski 1996). Sediment oxygen demand rates available in the literature ranged from 0 to 44 $\text{g/m}^2/\text{d}$, a maximum well in excess of that measured in the downstream reaches of the Assiniboine River and in the Red River. Sediment oxygen demand rates determined for this study through model calibration ranged from between 0 and 19 $\text{g/m}^2/\text{d}$ (Table 27) suggesting that calibrated rates exceeded those measured in the downstream reaches. Rates used in the three open water models

in this study were considerably higher on average (6.56, 8.26, and 11.95 g/m²/d) than those used in the one ice-covered model (0.18 g/m²/d). Higher calibrated SOD rates in this study compared to other studies may be due in part to the higher reaeration rates used for the upstream reaches. Reaeration rates during the open water season were calculated by the model to be between 1.83 and 36.62 /d. In comparison, Wesolowski (1994) set open water reaeration rates at 1.7 /d, considerably lower than those used in this study. Winter reaeration rates were also higher in this study (0.10 /d) as compared to the 0.05 /d used by Wesolowski (1996) and North *et al.* (2003).

Prescribed rates of NH₄ and inorgP flux from the benthos were included as part of the calibrated water quality models for the upper Assiniboine River. Prescribed rates of NH₄ flux ranged between 0 and 12 mgN/m²/d (average 4.06 mgN/m²/d) while inorgP flux ranged between 0 and 5.00 mgP/m²/d (average 2.37 mgP/m²/d). Average rates of both inorgP and NH₄ flux were highest in the summer and then varied without pattern through the remaining three seasons (Table 28). Benthic fluxes were one of only two model variables used in the N and P mass balance that could be varied across reaches. Although nutrient concentrations of incremental inflows could be varied, these were only manipulated when large fluctuations in constituents occurred over a very short spatial scale (*i.e.*, dramatic increase in turbidity within approximately 40 km downstream of Lake of the Prairies). Models developed for the downstream reaches of the Assiniboine River with QUAL2E (North *et al.* 2003, Cooley *et al.* 2001a) and for the Red River (Wesolowski 1994 and 1996) used reach-variable rates of ON hydrolysis, ON settling, and/or nitrification that could not be varied with QUAL2K. In contrast to many of the other rates, constants, and coefficients used in water quality modelling, model documentation for QUAL2E (Brown and Barnwell 1987) does not provide a range of suggested rates for NH₄ and inorgP flux from the benthos. Bowie *et al.* (1985) suggested that sediment release rates should be determined either through model calibration of dissolved nutrients or through models involving sediment nutrient release. Consequently, the upper Assiniboine River model included both prescribed rates determined through model calibration and internally simulated rates based on POM diagenesis.

10.2 Nitrogen and Phosphorus Budget in the Assiniboine River

Relative contributions of the four main sources of nutrients (headwaters at Lake of the Prairies, three main tributaries, incremental inflows or runoff, and sediment fluxes) to the upper Assiniboine River varied in each of the final models for spring, summer, fall, and winter (Table 29). During the summer modelling period, sediment and incremental inflow loads of N and P to the study reach greatly exceeded those from the three main tributaries and the headwaters. Since this period was characterized by very low discharge from Lake of the Prairies ($1.4 \text{ m}^3/\text{s}$) and some of the lowest discharges from all three tributaries, the dominance of runoff and benthic loads in the nutrient mass balance was not unexpected. However, even when the summer model was re-run with double the discharge from all three tributaries and Lake of the Prairies, runoff and benthic nutrient loads remained as the highest contributor to nutrients. An exception occurred for TOP where tributary inputs dominated the sources. Undoubtedly, during periods of relatively low discharge such as during the summer of 2002, within-stream, microbial mediated nutrient inputs and runoff dominated.

In the fall, patterns in nutrient loading were opposite to those observed in the summer with the majority of the N and P loads contributed by either Lake of the Prairies or the three tributaries (Table 29). While the majority of all fractions of N, TN, and TOP loads were contributed by Lake of the Prairies, most of the TP and inorgP loads were contributed by the three tributaries, followed closely by contributions from Lake of the Prairies. The relatively high contributions of N and P from Lake of the Prairies during the fall may be due to the release of nutrient rich-hypolimnetic waters into the Assiniboine River via the deep conduit in the outlet of Lake of the Prairies. Although Lake of the Prairies is relatively shallow with an annual mean depth of about 7 m, high rates of inorgP release from the sediments (typical of periods of oxygen stratification) were observed by Fortin and Gurney (1997). Although Fortin and Gurney (1997) did not observe prolonged stratification in Lake of the Prairies, bi-weekly sampling efforts may have missed short periods of stratification such as the 6 to 7 day periods observed by Riley and Prepas (1984) in two lakes in Alberta. Others have also observed a build up of NH_3 in deep waters during late summer-early fall due to reduced nitrification attributed to lowered oxygen concentrations, increased sediment oxygen demand, and a loss of nitrifying bacteria through zooplankton grazing (Wetzel 1983). Large loads of total organic N and P could be due to either

the release and build up of soluble ON and OP from the sediments in Lake of the Prairies or the influx of particulate ON and OP associated with a large summer algal population (mean 165 $\mu\text{g chl } a/\text{L}$, max 1470 $\mu\text{g chl } a/\text{L}$) into deeper waters during fall mixing. The presence of Lake of the Prairies, which is actually a reservoir with a control dam, greatly influences seasonal patterns in N and P loading with large loads of N and P provided to the headwaters of the Assiniboine River during the fall.

In the spring and winter, the largest contributor to the N or P load was not consistent (Table 29). Most of the TN and TON loads in the upper Assiniboine River were contributed by the three main tributaries during spring or by Lake of the Prairies in winter. Given that organic nutrient loads from the benthos (*i.e.*, from resuspension) could not be modelled with QUAL2K, the dominance of riverine and headwater loads was not unexpected. Although organic sources of N from resuspension were not included in the model, winter loads of TN and TON from Lake of the Prairies, the tributaries, and incremental inflows exceeded measured loads at Brandon suggesting all sources were measured. However, in spring, TN and TON loads from Lake of the Prairies, the tributaries, and incremental inflows could not account for the load measured at Brandon suggesting sources of ON were missing from the model.

Similar to TON loads, most of the TOP load during spring and winter was contributed by the three main tributaries. In contrast, most of the inorgP and TP loads in spring and winter were derived from the benthos or were input into the river as incremental inflows. During winter, most of the NH_3 load came from the benthos while NO_2NO_3 was derived primarily from the tributaries. However, during spring, most of the NH_3 load was derived from the tributaries while most of the NO_2NO_3 load came from sediment and incremental inflows. Although there was not a consistent major contributor, during spring and winter, each of the four main sources of nutrients formed a critical portion of the overall nutrient budget in the Assiniboine River.

The sum of the four major sources of nutrients (headwaters at Lake of the Prairies, three main tributaries, incremental inflows or runoff, and sediment fluxes) provided an estimate of the total input of nutrients to the upper Assiniboine River for each season. The mass of nutrients exported from the overall study reach was estimated based on the load measured at Brandon. In general, nutrient inputs to the Assiniboine River exceeded that measured at Brandon. While

nutrient sources may have been overestimated (particularly for incremental inflows and benthic flux which were estimated by the model) the Assiniboine River may also retain nutrients between Lake of the Prairies and Brandon. In particular, the final models predicted that between 81 and 12 % of the DIN input into the Assiniboine River was retained with most retention occurring during summer and little retention occurring during winter. Peterson *et al.* (2001) also observed high DIN retention in streams across the US during periods of high biotic activity. However, they predicted that over an annual cycle the stored N would be exported as regenerated inorganic, gaseous, or organic N. While the four seasonal Assiniboine River models suggested DIN was retained all year, TON exported at Brandon during spring and summer exceeded inputs to the stream between Lake of the Prairies and Brandon. Perhaps N stored in the inorganic form throughout the year was released as TON during spring and summer. Where nutrient loads measured at Brandon exceed those from the four main sources, incremental inflows and sediment flux may have been underestimated. Relatively small under- or overestimations in sediment fluxes could be expected since the final models were designed to provide accurate and precise results for as many scenarios as possible during each particular season rather than optimising predictions for the final period chosen.

Similar patterns existed for inorgP with between 23 and 53 % of the input into the upper Assiniboine River retained during the three open water seasons. In contrast, the Assiniboine River was a net exporter of inorgP during the winter modelling period. Organic P retained during the winter and spring may be exported during the summer and fall when exports of TOP exceeded those accounted for by the four main sources of nutrients.

When model predicted import and export from the study reach was compared, the upper Assiniboine River retained N during winter, summer and fall, but was a net exporter of N during spring. Conversely, P was retained during winter through summer and exported in the fall. Both periods of net export were associated with export of organic rather than the inorganic fractions of N and P. Inorganic fractions of N and P were generally retained. Assuming similar patterns occurred across the entire season, the Assiniboine River study reach retains both N and P on an annual basis with about 14.6 and 20.1 % of the N and P retained, respectively. Bourne *et al.* (2002) found that the Assiniboine River retained both N and P during the period between 1994 and 2001. Grizetti *et al.* (2003) noted that more P was retained than N over an annual cycle in

the Vantaanjoki basin in Finland. Retention in the Vantannjoki basin (24 % N, 51 % P) was greater than observed in the study reach but modelling was based on a longer time period (9 years) with a daily time step. Also, retention is based in part on the size of the water body and on discharge conditions with headwater streams generally retaining more nutrients than larger rivers. Given that the Vantaanjoki basin is much smaller (1,680 km²) than the study area (more than 14,000 km²) lower retention in the Assiniboine River basin could be expected. Of critical importance is the ability of the Assiniboine River to continue to retain N and P. As part of the Lake Winnipeg watershed, nutrients transported downstream of Brandon have the potential to enter Lake Winnipeg through the Red River. Peterson *et al.* (2001) suggested that the capacity of streams to effectively retain N decreases as N inputs to streams increase. Future developments in the study area that increase the potential for N input to the Assiniboine River may overwhelm N (and possibly P) retention thereby increasing nutrient loads in receiving waters such as Lake Winnipeg.

10.3 Nitrogen and Phosphorus Limitation in the Upper Assiniboine River

10.3.1 TN to TP Ratios

Total N to TP ratios have been used throughout the literature to indicate nutrient deficiency because the ratio correlates well with other measures of nutrient deficiency (Dodds 2003). Smith (1982) suggested that algal biomass is N limited when TN:TP by mass is < 10 whereas P is limiting when TN:TP > 17. Throughout the three year study, TN:TP ratios ranged between 2.0 and 67.7 in the Assiniboine River suggesting periods of both N and P limitation. As no differences were detected in TN:TP ratios between 2001, 2002, or 2003, further analyses were conducted on pooled samples ($P > 0.05$). However, differences between seasons were detected. Periods of ice-cover were characterized by relatively higher TN:TP ratios (26.6) on average ($P < 0.0001$) compared to open water periods (15.4) suggesting that P deficiency dominated in winter while summer was characterized by periods of N and P limitation. Co-N and P limitation also existed during times when the ratio was between 10 and 17. Based on the TN:TP ratios, about one third of the open water season was characterized by P limitation, one third by N limitation, and the remaining third by co-limitation. Differences between months during the open water season were also detected ($P < 0.0001$). Except for April, June, and July, all months were

characterized by TN:TP ratios between 10 and 17 suggesting co-nutrient limitation. While TN:TP ratios for April (18.6) and June (22.7) were characterized by P limitation and July was characterized by N limitation (9.4), in most instances, ratios were on the border of established limits. Within the ice-free season, TN:TP ratios were correlated with distance downstream of Lake of the Prairies ($r^2 = 0.56$, $P < 0.0010$) such that P limitation decreased with distance downstream. Based on TN:TP ratios, algal biomass was P limited during periods of ice-cover with the open water season characterized by periods of distinct P and N limitation as well as periods of co-limitation.

10.3.2 Model Prediction of N and P Limitation

Assessment of model-derived, algal growth limitation factors indicated that periods of light, nitrogen, or phosphorus limitation occurred in the Assiniboine River throughout the modelled periods. During winter, algal biomass in the Assiniboine River was light-limited. Due to the shorter periods of daylight, reduced solar radiation, and ice-cover, this could be expected. When only nutrients were considered, similar to conclusions derived from the TN:TP ratios, P was the most limiting nutrient during the ice-covered season. Conversely, during all three ice-free seasons, model-derived algal growth limitation factors suggested that N rather than P limited algal biomass. However, light limitation was also a factor during the ice free seasons. In spring, algal biomass was light limited during the early and late hours of the day. The number of hours of light-limitation was directly correlated with depth of the reach such that reaches deeper than approximately 1 m were light limited for all but about 4 hours between 2 and 6 PM. During summer, periods of light-limitation were more common than in the spring. In the 21 deepest reaches, algal biomass was light limited at all times of the day whereas in the remaining shallower reaches, light limitation occurred for all but the periods of intense light during the mid-day when N was limiting. During fall, algal biomass was light limited at all times of the day until just upstream of Virden (river km 291.5) where N limitation gradually increased for most hours of the day except when solar radiation was low during approximately the first and last half hours daylight. Nitrogen supplied by the Little Saskatchewan River resulted in a return to light limitation of algal biomass downstream of the confluence with the Assiniboine River (river km 435). While TN:TP ratios provide information on algal growth limitation by N and P, model predictions provided additional information on light limitation. In the upper Assiniboine River

over the study period, light limited algal biomass through much of the ice-covered and open water seasons. As suggested by the TN:TP ratios, phosphorus was the primary nutrient limiting algal biomass during the ice-covered season. However, while TN:TP ratios suggested periods of either N or P limitation, the model predicted that nitrogen was the primary nutrient limiting algal biomass during the open water seasons.

10.3.3 Longitudinal Trends in N and P Concentrations in the Upper Assiniboine River

Longitudinal patterns of N and P concentrations in the Assiniboine River also suggested that nitrogen was the primary nutrient limiting algal biomass. In general, TP and inorgP concentrations followed a predictable trend of increasing concentration between Lake of the Prairies and Brandon (*e.g.*, Figures 29 and 30). The predictable trend made P relatively easy to model with about 63 % of the observed TP, TOP, and inorgP concentrations modelled with high precision in the 21 different initial and test water quality models developed for the upper Assiniboine River. In contrast, TN, TON, NH_3 , and NO_2NO_3 concentrations along the Assiniboine River were much more variable (*e.g.*, Figures 33 and 34). Ammonia concentrations increased and decreased as much as 0.30 mg/L between sampling stations while NO_2NO_3 concentrations varied up to 1.49 mg/L between stations. The large, irregular variability in N concentrations between stations made modelling more difficult. Only 34 % of the observed TN, TON, NH_3 , and NO_2NO_3 concentrations were modelled with high precision in the 21 different initial and test water quality models developed for the upper Assiniboine River. The variability in nitrogen concentrations provides support for the hypothesis that N rather than P limits algal biomass in the Assiniboine River. Dent and Grimm (1999) suggest that the limiting nutrient (in their study nitrogen) was consistently more variable and patchy than other variables studied (phosphorus or conductivity).

Given the number of physical, biological, and chemical processes that can impact nitrogen concentrations in the Assiniboine River (*e.g.*, autotrophic uptake, denitrification, nitrification, mineralization, resuspension and settling, and benthic flux) variability in concentrations of the various fractions is not unexpected. In addition, nitrogen in rivers is continually transported downstream such that each N molecule spirals through the N cycle as it moves downstream (Newbold *et al.* 1981). Factors affecting nutrient uptake length (the average

downstream distance that a molecule travels before being removed from the water column through uptake) such as algal species and biomass, inputs of organic matter, and channel morphology likely also affect spatial patterns in nutrient concentrations (Dent and Grimm 1999). Added to the complexity of nutrient spiralling are point and non-point source N loading from the watershed. As such, explanation of N concentrations in streams requires analyses of a wide range of physical, chemical, and biological within stream and within watershed processes.

11.0 Future Water Quality Model Applications

The final water quality models developed in this study for the Assiniboine River can be used to assess the impact of changes in climate variables (precipitation, air temperature), discharge regulation (discharge from Lake of the Prairies and the Qu'Appelle River basin), point sources (additional development in the study area with discharge to the Assiniboine River or the three main tributaries), and water chemistry of incremental inflows or runoff. Results and potential implications associated with final water quality model assessment can be demonstrated by looking at the question "what are the downstream impacts associated with an increase in discharge from Lake of the Prairies?" Inorganic phosphorus concentrations were examined under three different discharge scenarios from the outlet of Lake of the Prairies (2.8, 8.5, and 14.2 m³/s) during all four seasons.

Modelled inorgP concentrations demonstrated a seasonal response to changes in discharge from Lake of the Prairies. During spring, summer, and winter, inorgP concentrations across the study reach declined as discharge from Lake of the Prairies was increased from 2.8 to 14.2 m³/s (e.g., Figure 132). Given that Lake of the Prairies contributes less than 21 % of the total inorgP to the study reach during spring, summer, and winter, increased discharge through the outlet of Lake of the Prairies diluted downstream inorgP concentrations. In contrast, during the fall, inorgP concentrations along the study reach increased as discharge from Lake of the Prairie was increased from 2.8 to 14.2 m³/s (Figure 133). Since inorgP concentrations at Lake of the Prairies were relatively high during the fall and because the headwaters contributed about 33 % of the inorgP load to the Assiniboine River, larger discharges from the outlet of Lake of the Prairies seemed to enhance rather than dilute P concentrations. In particular, just upstream of Miniota (river km 215) inorgP concentrations at a discharge of 14.2 m³/s were about double

those predicted when the discharge was $2.8 \text{ m}^3/\text{s}$. Given that concentrations of other constituents such as NH_3 were also relatively high at the outlet of Lake of the Prairies during the fall period, similar patterns of enhanced downstream concentrations may be observed when discharge from the outlet of Lake of the Prairies are increased during this season. Perhaps regulation of discharge from Lake of the Prairies should consider the potential for high reservoir nutrient loads in fall to supplement downstream loads.

12.0 Conclusions

Four water quality models were developed for the Assiniboine River between Lake of the Prairies and the City of Brandon representing three open water seasons (spring, summer and fall), and one ice-covered season. Each final model was calibrated and tested on at least four independent sampling periods to test the robustness of the model within the range of physical, chemical, and biological conditions observed during the 2001 to 2003 study. Model calibration as measured by accuracy and precision was most successful for dissolved oxygen and both inorganic and total P. Fall and spring periods were modelled with high precision and accuracy. In contrast, summer periods were difficult to model due to the need for reach variable light extinction coefficients and stoichiometric ratios that could not be included in QUAL2K. Periods of transition between ice-covered and ice-free periods such as December and April were also difficult to model due to rapid changes in temperature, aeration, and incremental inflows across the travel time. The final models provide a mechanism for testing the impact of future changes within the watershed due to climate change, development, or river management. However, future model predictions must be interpreted with caution since conditions outside those tested and calibrated may be controlled by factors not considered during development of these models.

Development of the water quality models also provided an indication of overall water quality within the Assiniboine River between Lake of the Prairies and the City of Brandon such that:

- Chronic and acute water quality objectives for total ammonia were met at all times during the study on the Assiniboine River and its tributaries.

- Acute water quality objectives for DO were met 95 % of the time in the Assiniboine River with all but one of the exceedances occurring during the open water season. Chronic water quality objectives for DO were met 88 % of the time in the Assiniboine River. In the three main tributaries to the Assiniboine River, acute water quality objectives for DO were met during all but one instance each on Birdtail Creek and the Qu'Appelle River. Chronic water quality objectives for DO were met 85 % of the time with the majority of exceptions occurring on the Little Saskatchewan and Qu'Appelle rivers.
- Algal biomass in the Assiniboine River was limited primarily by light with phosphorus as the primary nutrient limiting algal biomass during the winter and nitrogen limiting in the open water season.
- Each of the main sources of N and P to the water quality model (Lake of the Prairies, the three main tributaries, benthic flux, and incremental inflow (runoff)) was the primary source of nutrients to the upper Assiniboine River during one of the four seasons modelled.
- Strong, seasonal differences in the dominant source of nutrients to the upper Assiniboine River may impact management decisions such that incremental and benthic sources could be targeted in summer while control of discharge from Lake of the Prairies may provide a mechanism for nutrient reductions in the fall.
- Annual extrapolation of seasonal water quality models suggests that the upper Assiniboine River between Lake of the Prairies and the City of Brandon provides net retention of N and P.

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TABLES AND FIGURES

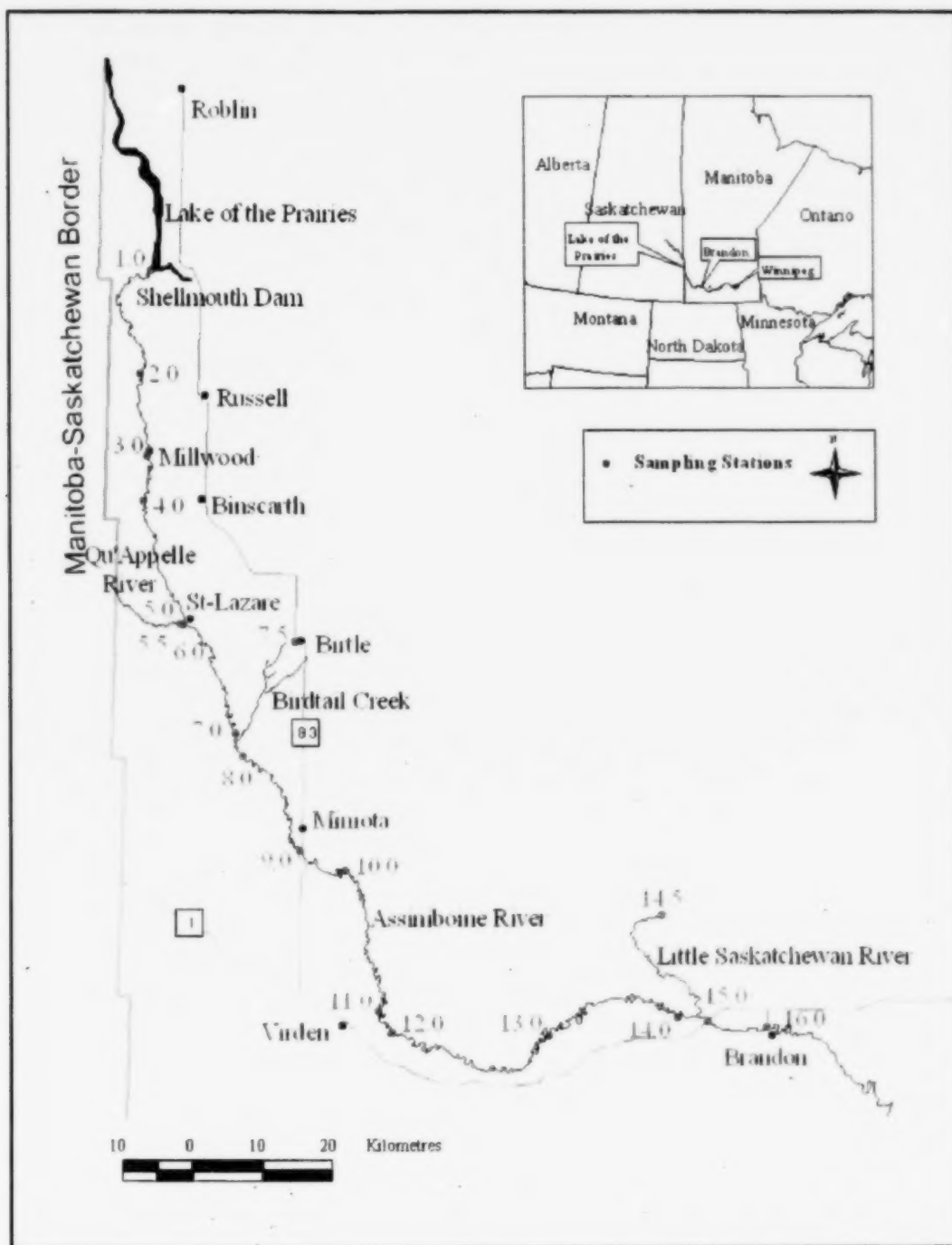


Figure 1. Water quality sampling stations between Lake of the Prairies and the City of Brandon on the Assiniboine River and major tributaries (2001 to 2003).

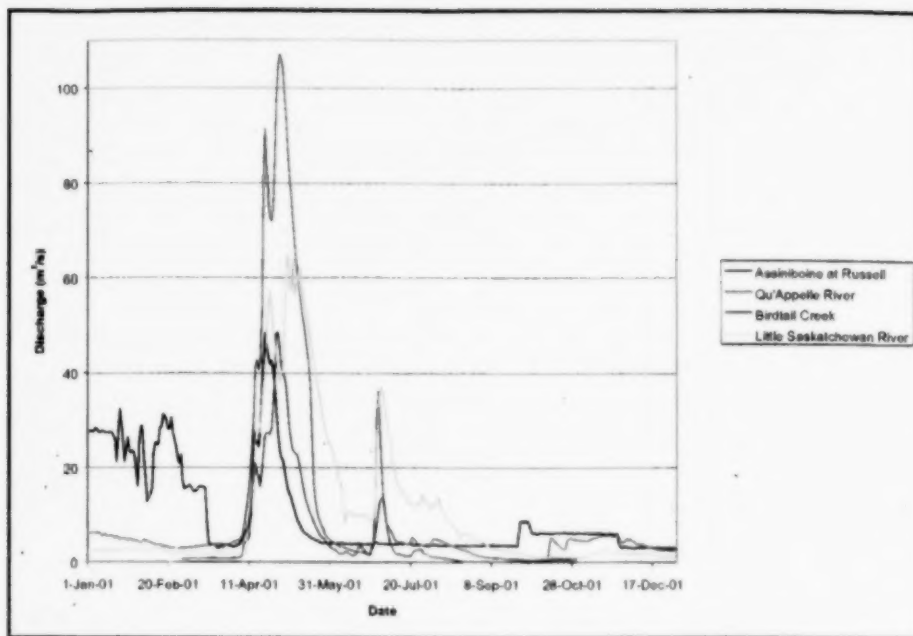


Figure 2. Discharge during 2001 in the Assiniboine River at Russell, in the Qu'Appelle and Little Saskatchewan rivers, and in Birdtail Creek (note scale compared to Figure 3).

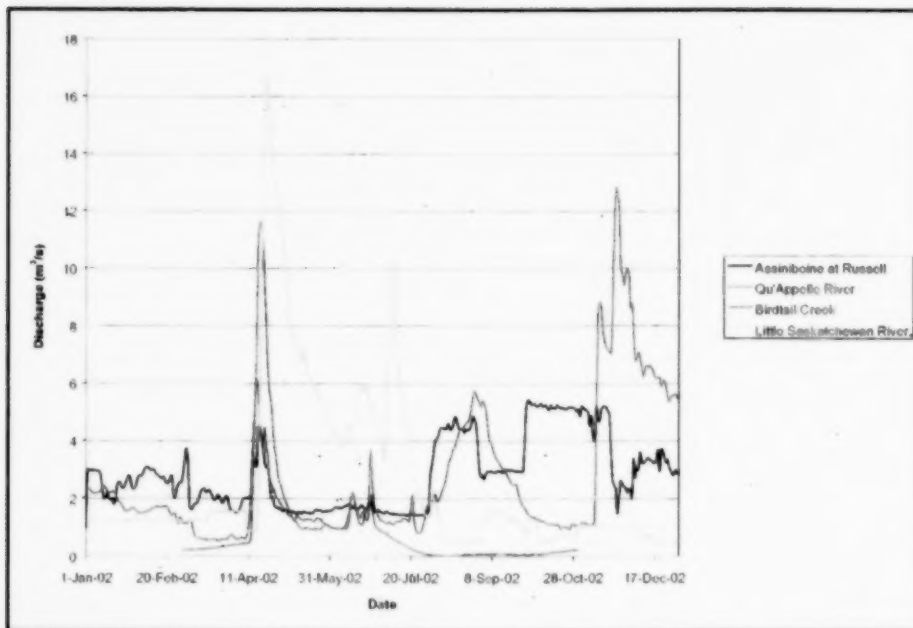


Figure 3. Discharge during 2002 in the Assiniboine River at Russell, in the Qu'Appelle and Little Saskatchewan rivers, and in Birdtail Creek (note scale compared to Figure 2).

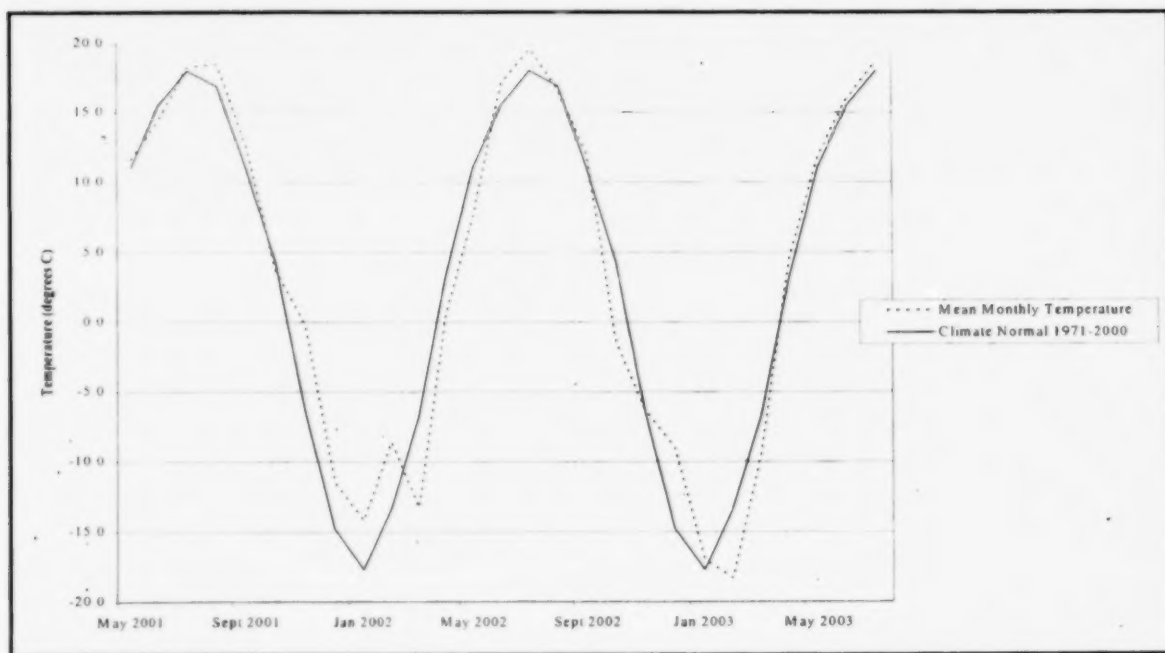


Figure 4. Mean monthly temperature for the study period and the Canadian climate normals for Binscarth, Manitoba (Environment Canada 2003b).

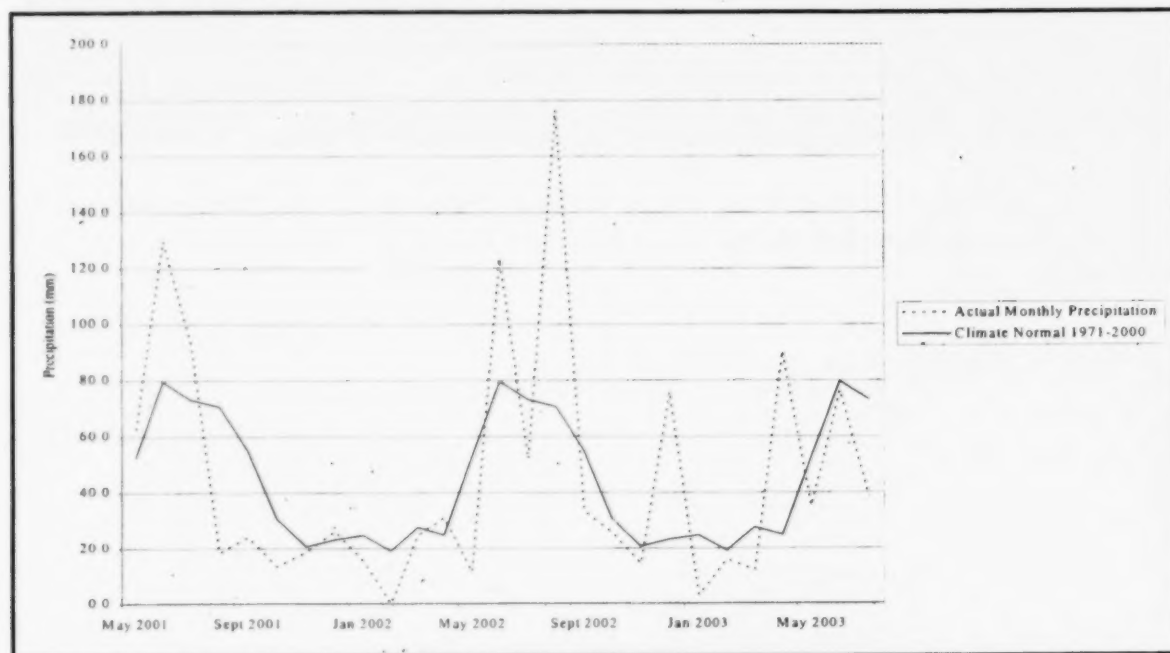


Figure 5. Total monthly precipitation for the study period and the Canadian climate normals for Binscarth, Manitoba (Environment Canada 2003b).

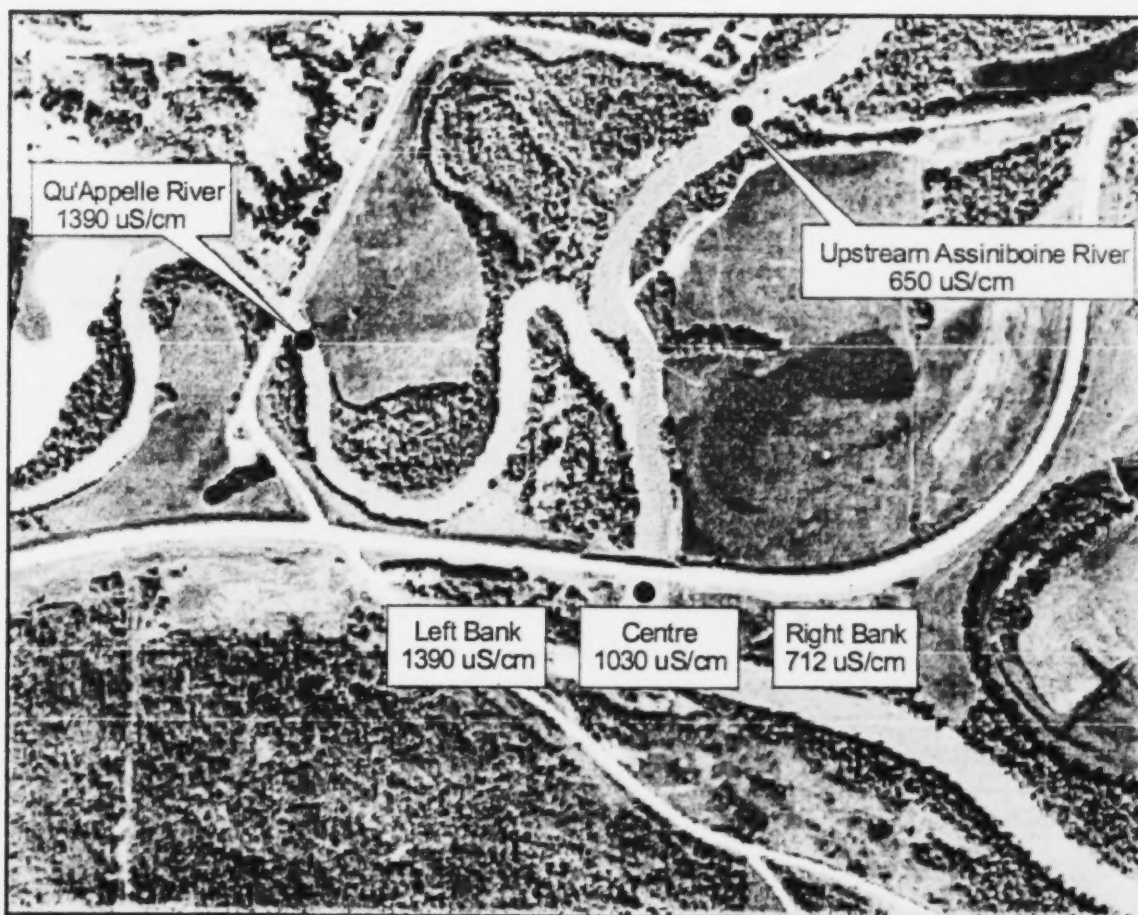


Figure 6. Variation in conductivity across the Assiniboine River just downstream of the confluence with the Qu'Appelle River, July 2003.

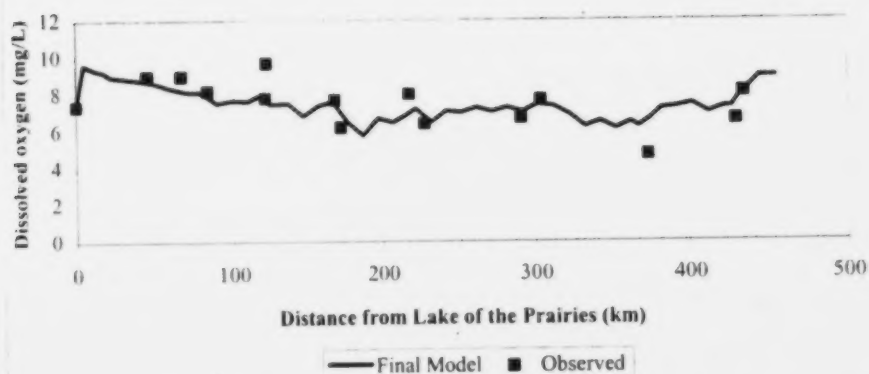


Figure 7. Change in dissolved oxygen concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

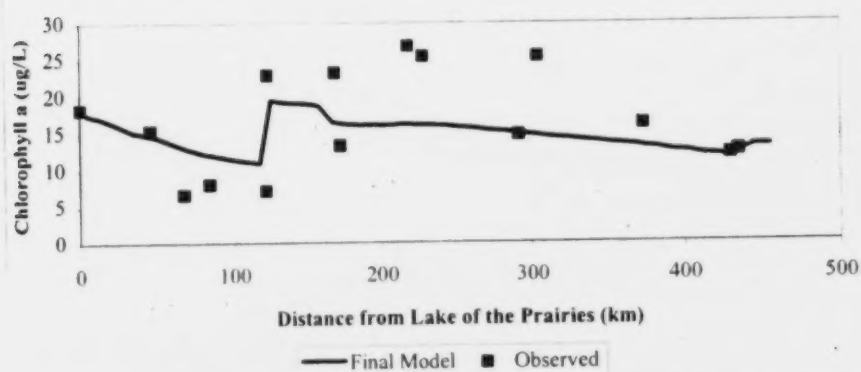


Figure 8. Change in chlorophyll *a* concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

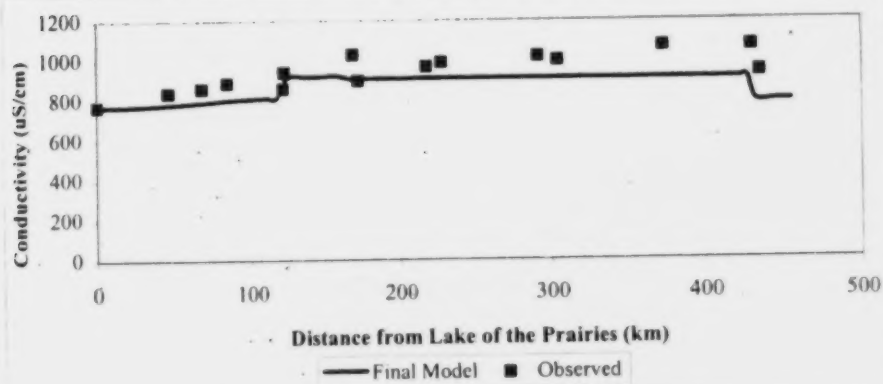


Figure 9. Change in conductivity concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

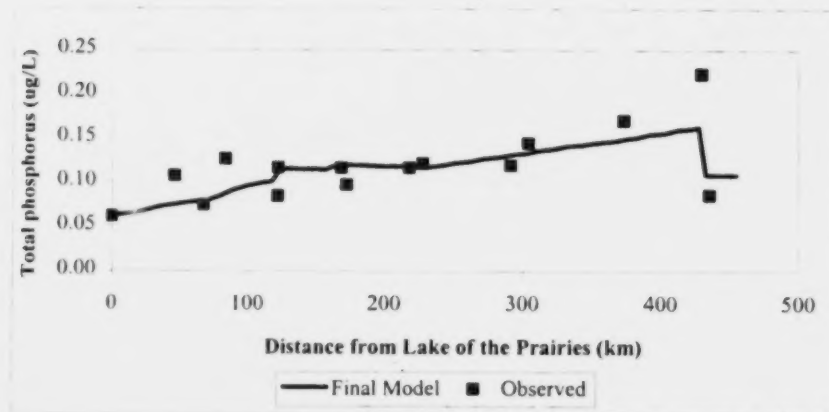


Figure 10. Change in total phosphorus concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

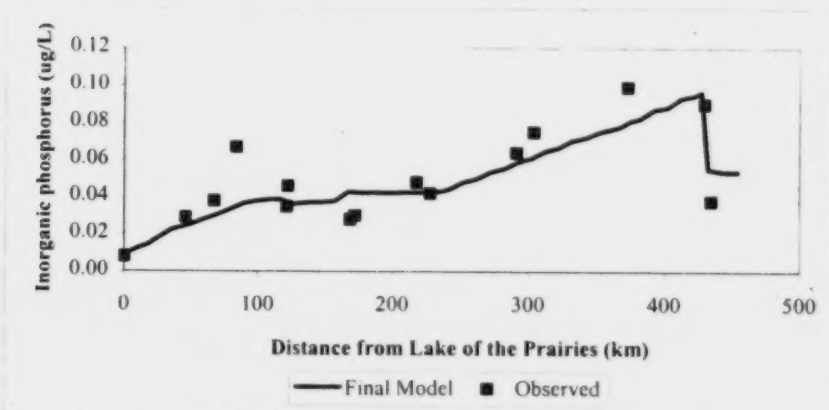


Figure 11. Change in inorganic phosphorus concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

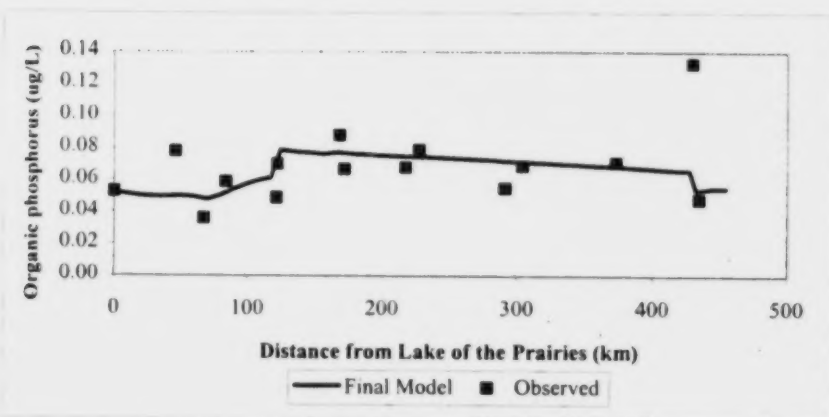


Figure 12. Change in organic phosphorus concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

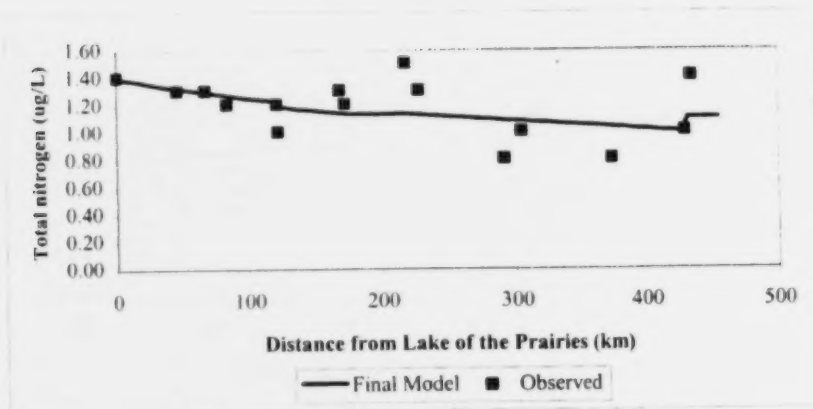


Figure 13. Change in total nitrogen concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

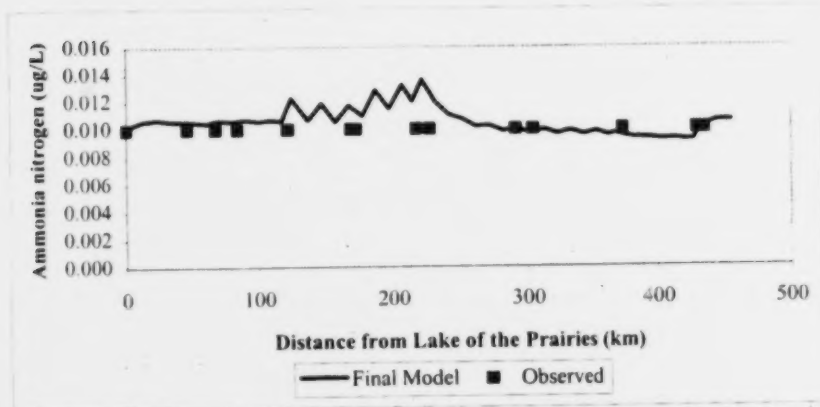


Figure 14. Change in ammonia concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

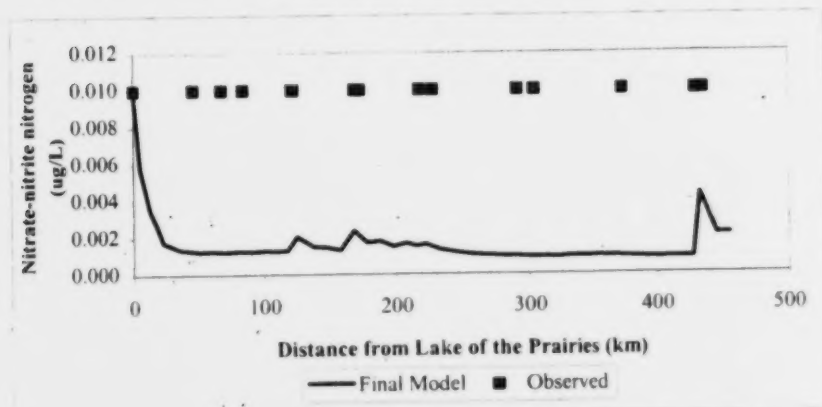


Figure 15. Change in nitrite-nitrate concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

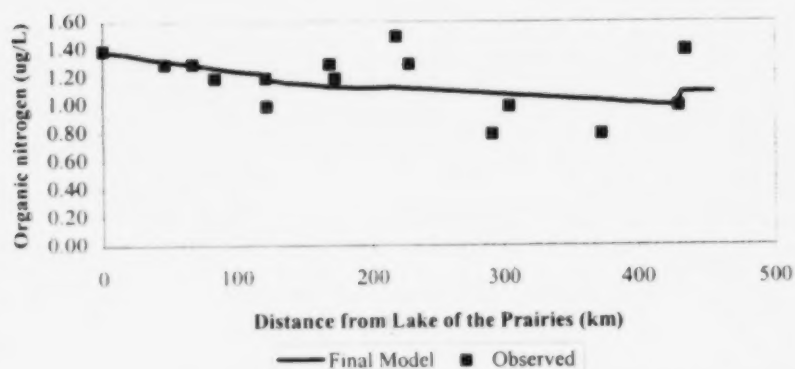


Figure 16. Change in organic nitrogen concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

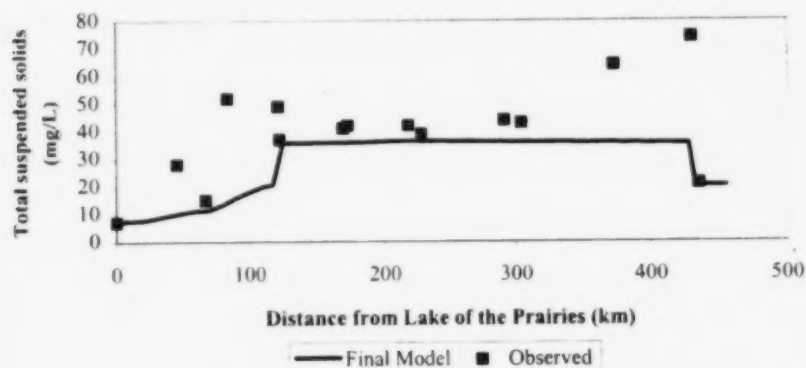


Figure 17. Change in total suspended solids concentrations during June 5 2002 with distance downstream from Lake of the Prairies.

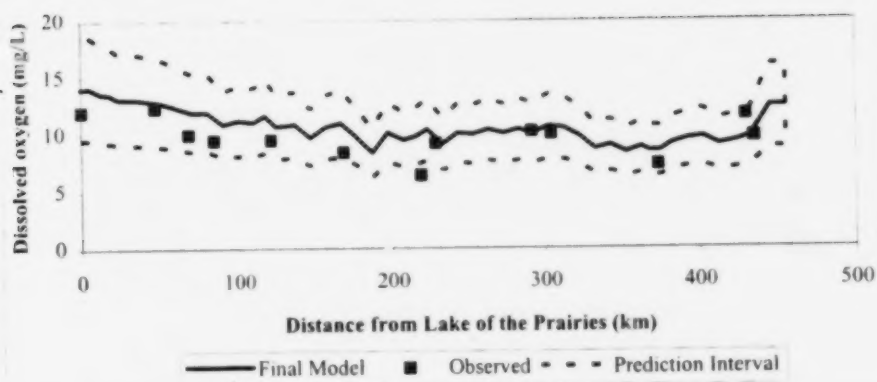


Figure 18. Change in dissolved oxygen concentrations during May 9 2002 with distance downstream from Lake of the Prairies.

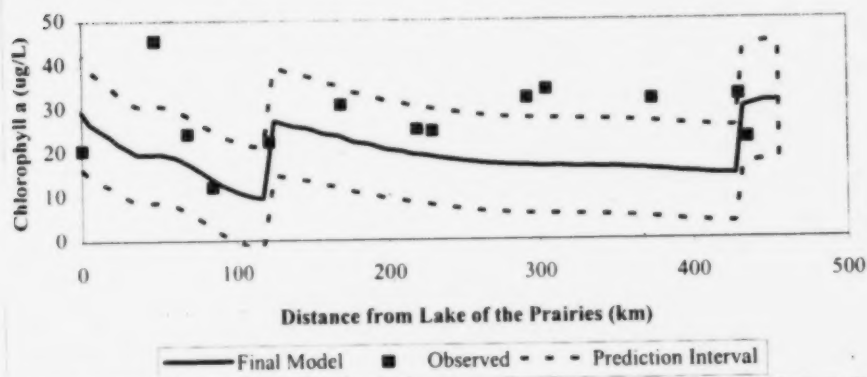


Figure 19. Change in chlorophyll a concentrations during May 9 2002 with distance downstream from Lake of the Prairies.

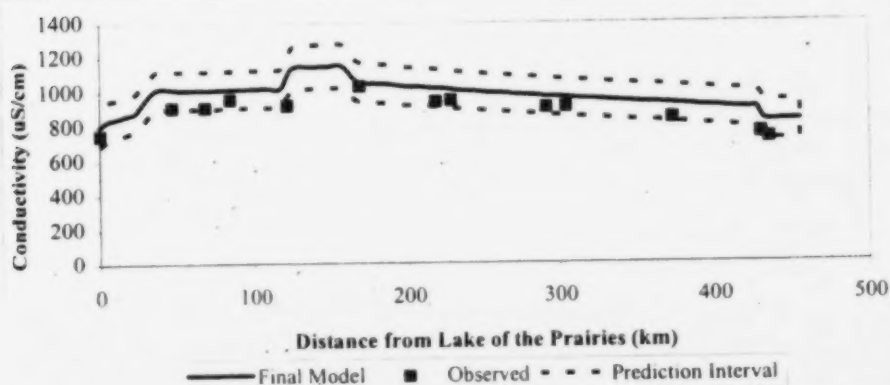


Figure 20. Change in conductivity concentrations during May 9 2002 with distance downstream from Lake of the Prairies.

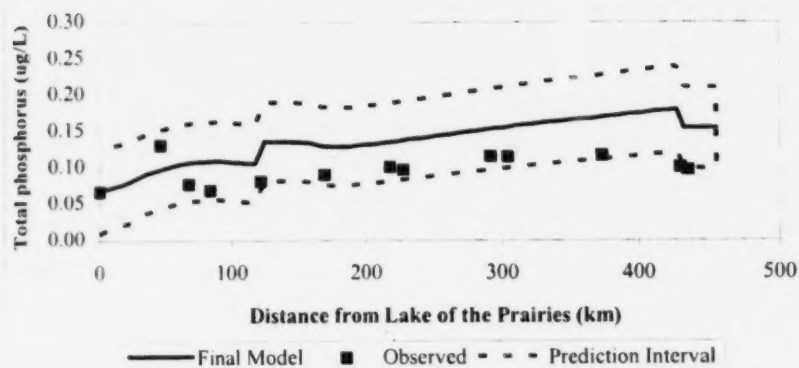


Figure 21. Change in total phosphorus concentrations during May 9 2002 with distance downstream from Lake of the Prairies.

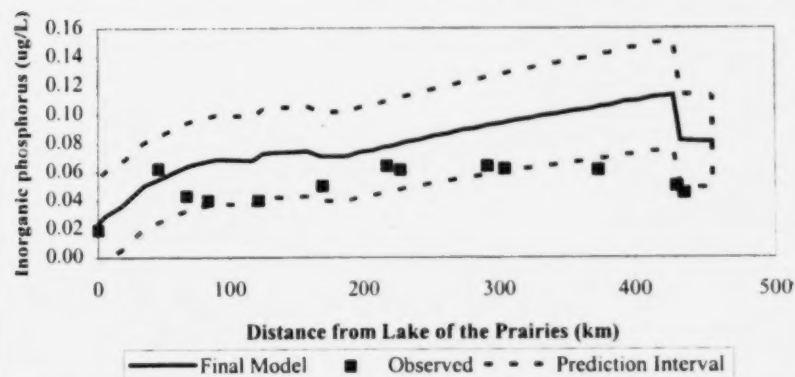


Figure 22. Change in inorganic phosphorus concentrations during May 9 2002 with distance downstream from Lake of the Prairies.

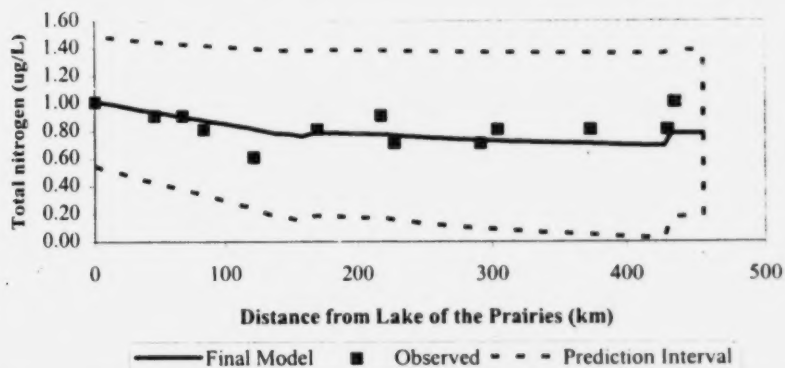


Figure 23. Change in total nitrogen concentrations during May 9 2002 with distance downstream from Lake of the Prairies.

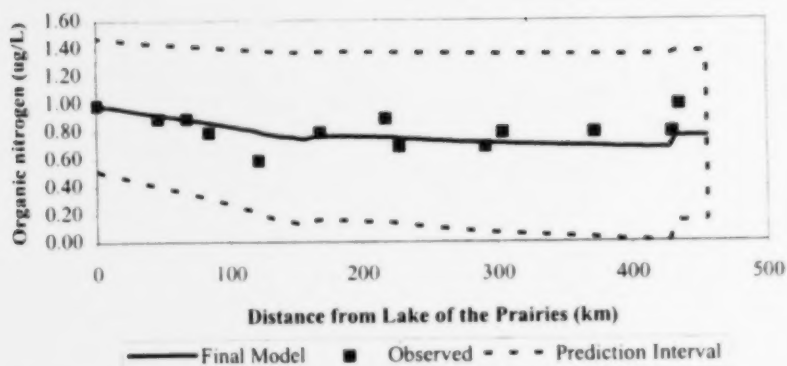


Figure 24. Change in organic nitrogen concentrations during May 9 2002 with distance downstream from Lake of the Prairies.

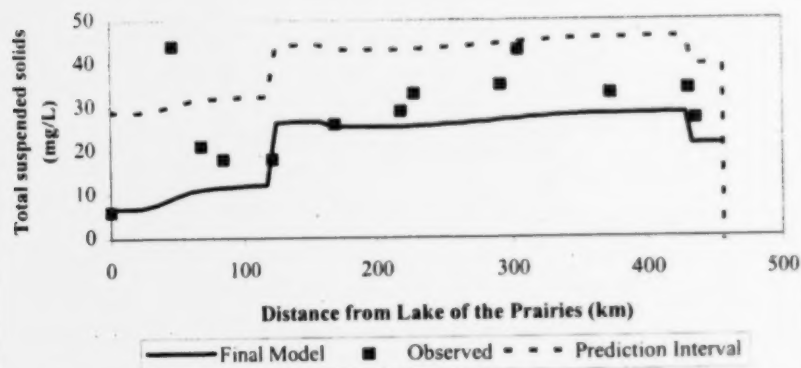


Figure 25. Change in total suspended solids concentrations during May 9 2002 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).

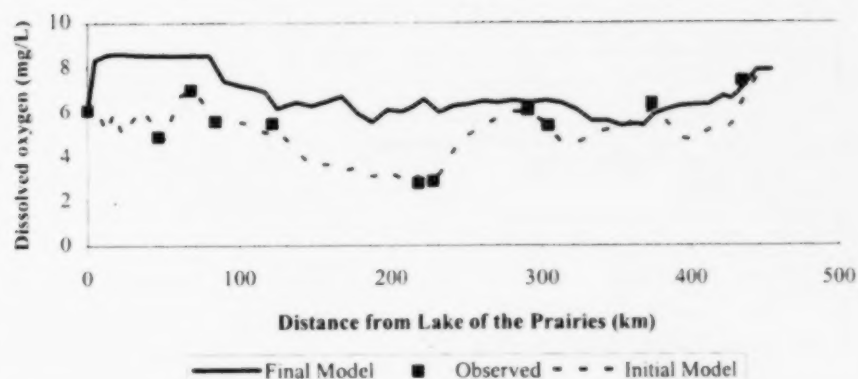


Figure 26. Change in dissolved oxygen concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

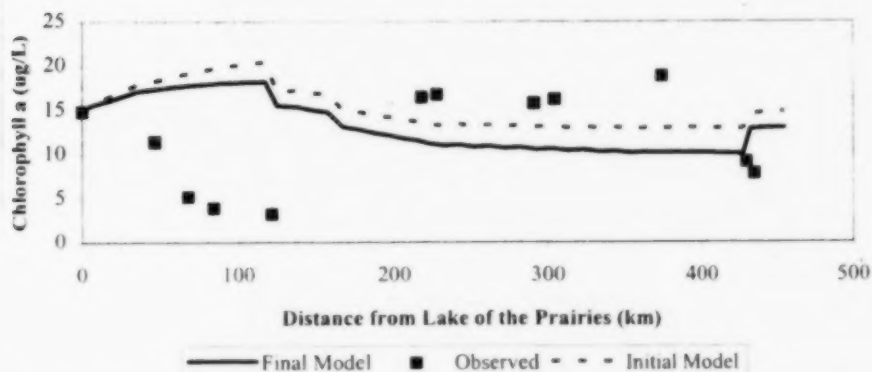


Figure 27. Change in chlorophyll a concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

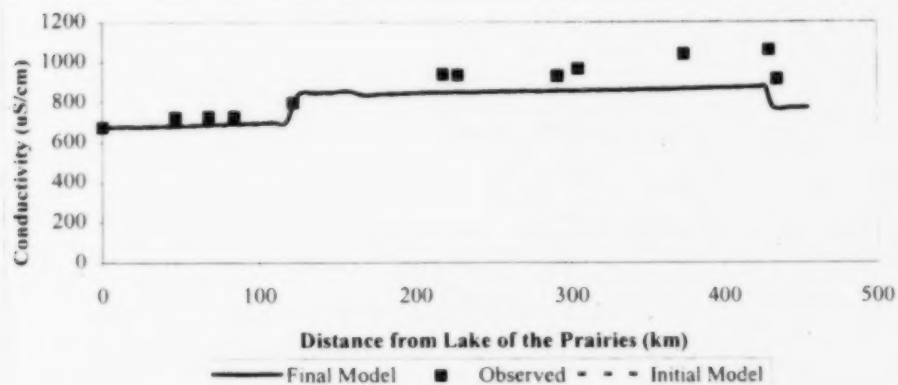


Figure 28. Change in conductivity concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

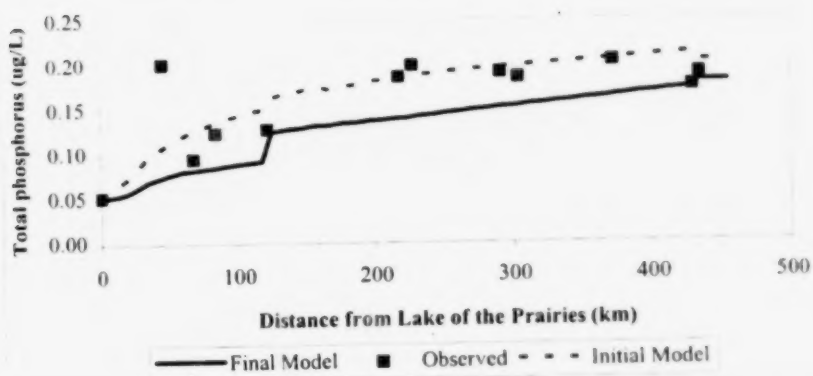


Figure 29. Change in total phosphorus concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

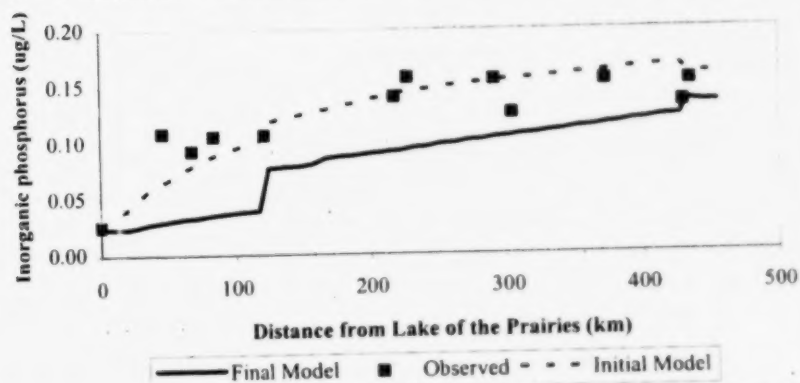


Figure 30. Change in inorganic phosphorus concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

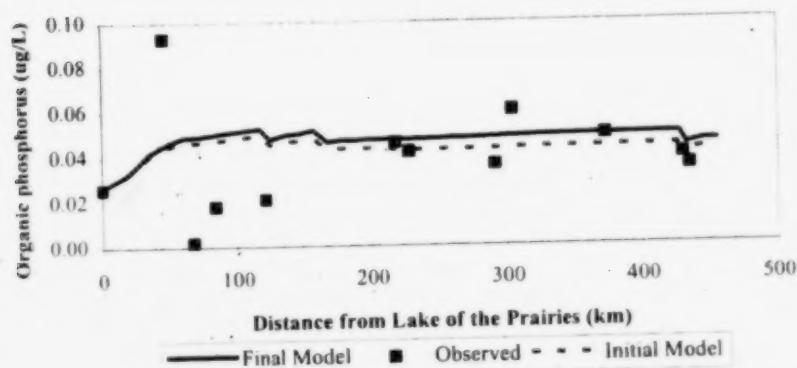


Figure 31. Change in organic phosphorus concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

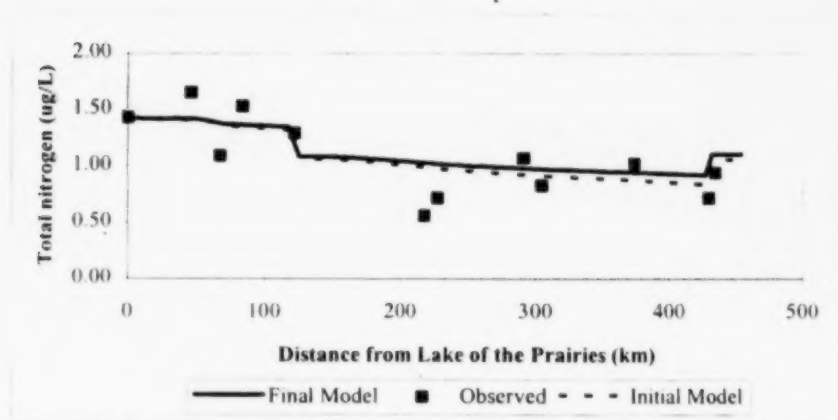


Figure 32. Change in total nitrogen concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

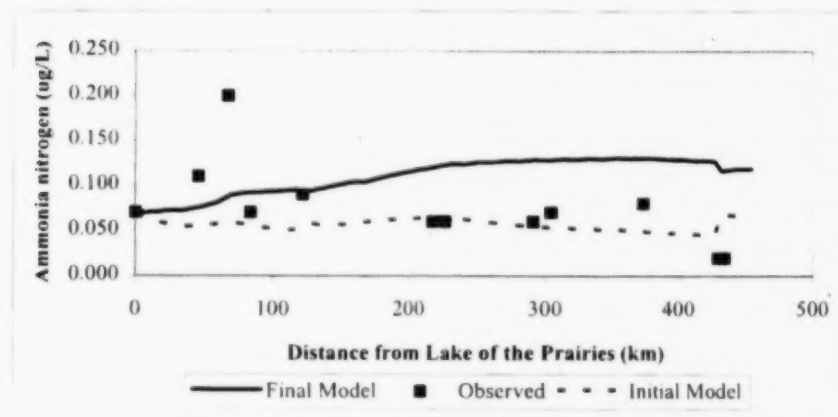


Figure 33. Change in ammonia concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

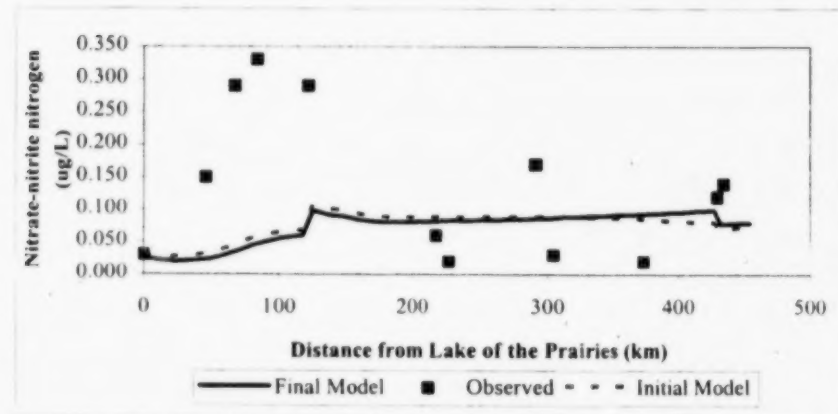


Figure 34. Change in nitrite-nitrate concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

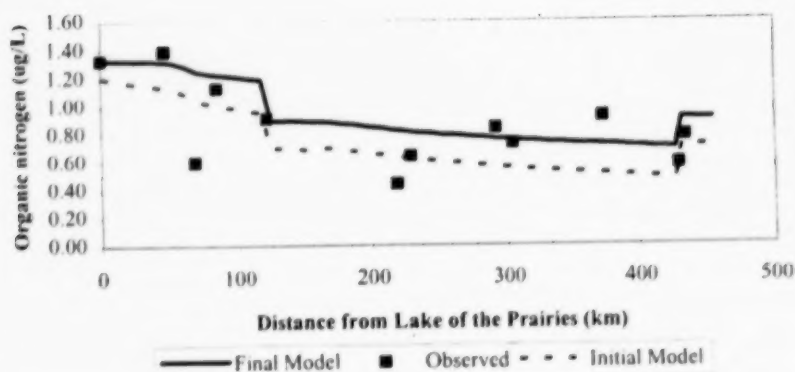


Figure 35. Change in organic nitrogen concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

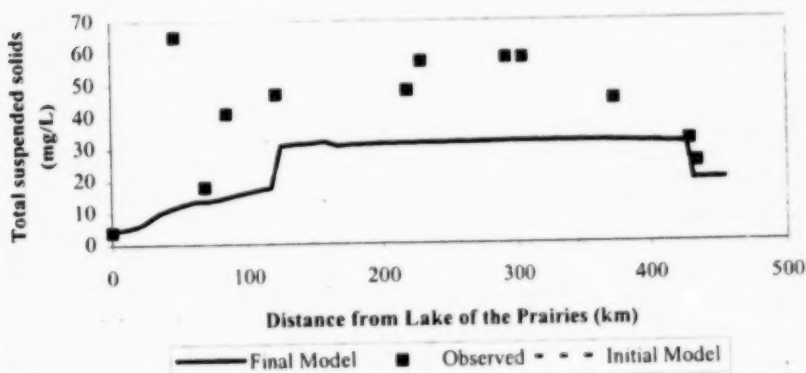


Figure 36. Change in total suspended solids concentrations during July 25 2001 with distance downstream from Lake of the Prairies.

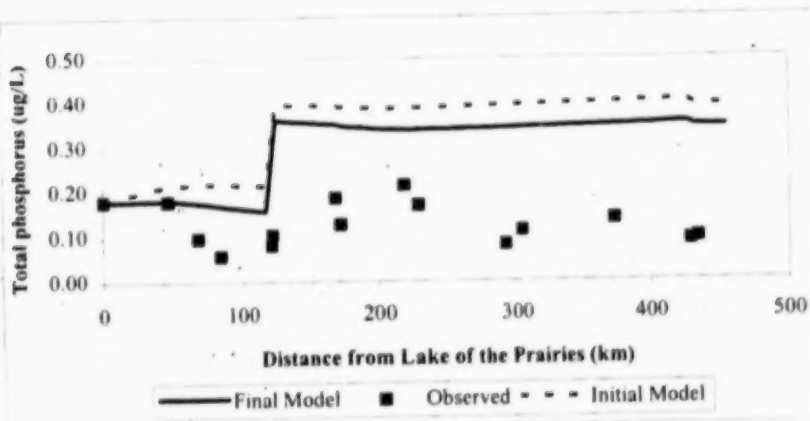


Figure 37. Change in total phosphorus concentrations during August 21 2002 with distance downstream from Lake of the Prairies.

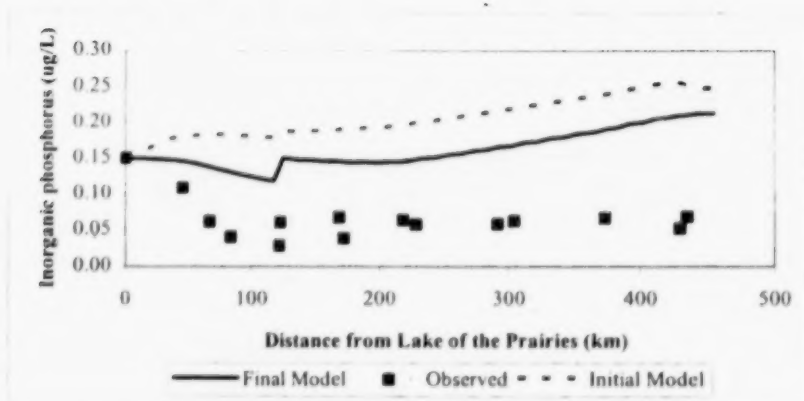


Figure 38. Change in inorganic phosphorus concentrations during August 21 2002 with distance downstream from Lake of the Prairies.

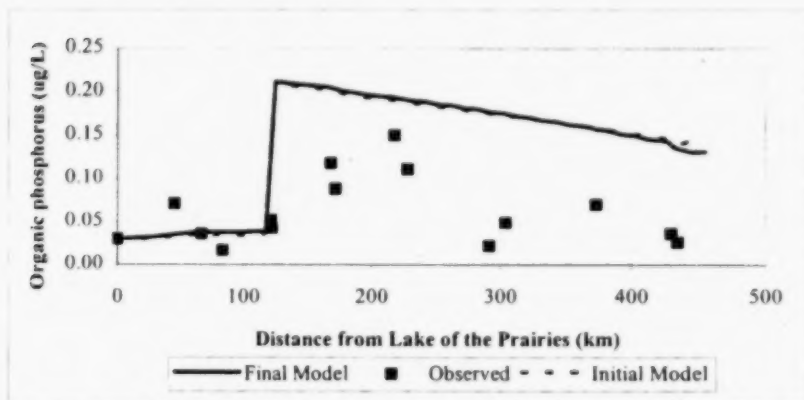


Figure 39. Change in organic phosphorus concentrations during August 21 2002 with distance downstream from Lake of the Prairies.

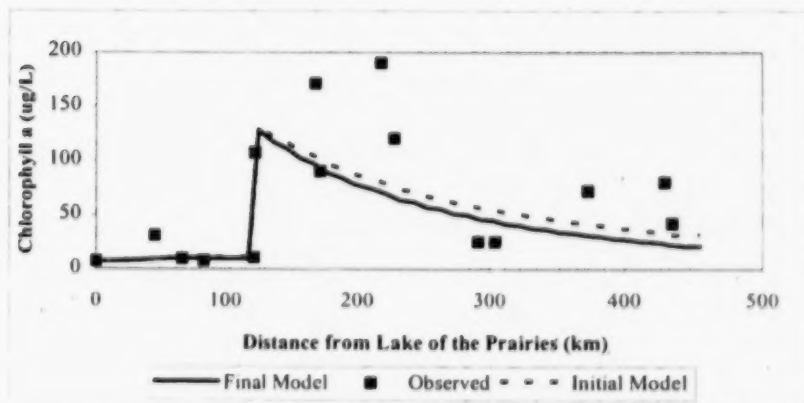


Figure 40. Change in chlorophyll a concentrations during August 21 2002 with distance downstream from Lake of the Prairies.

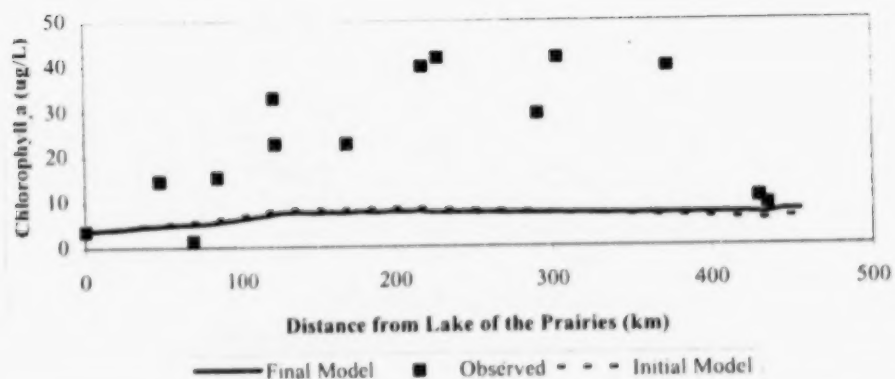


Figure 41. Change in chlorophyll a concentrations during August 7 2002 with distance downstream from Lake of the Prairies.

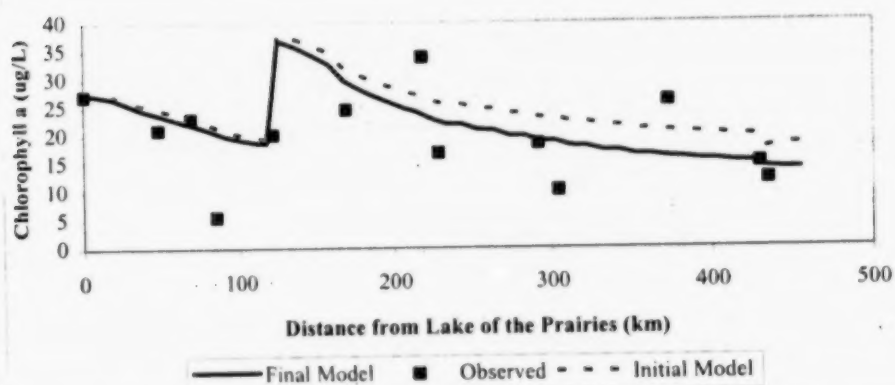


Figure 42. Change in chlorophyll a concentrations during August 8 2001 with distance downstream from Lake of the Prairies.

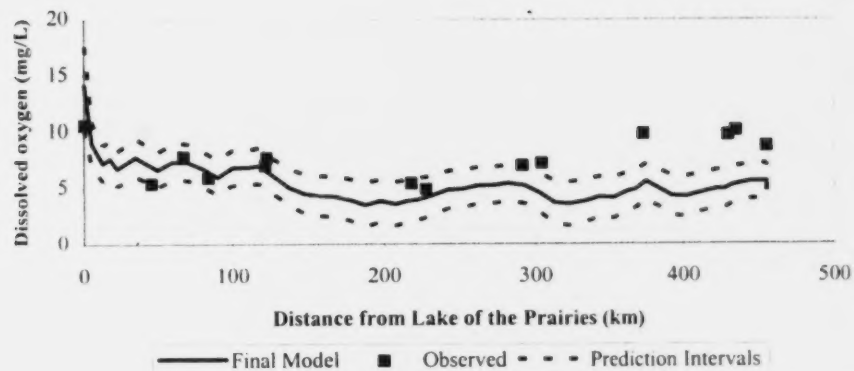


Figure 43. Change in dissolved oxygen concentrations during July 16 2003 with distance downstream from Lake of the Prairies.

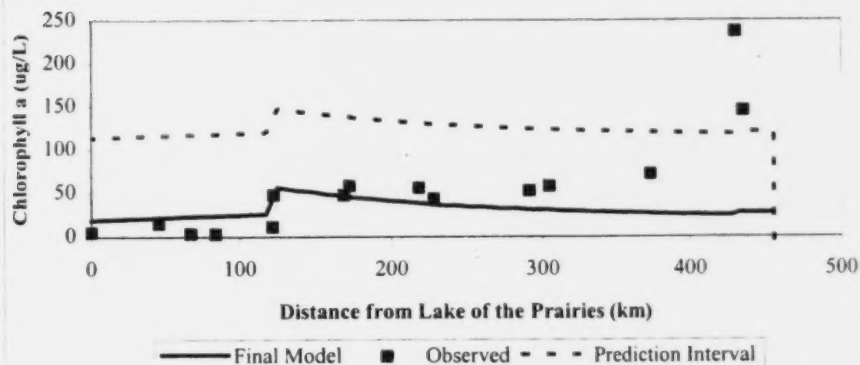


Figure 44. Change in chlorophyll a concentrations during July 16 2003 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).

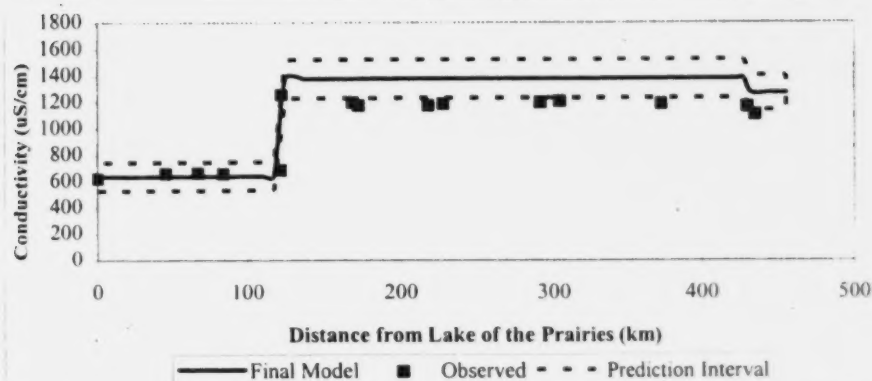


Figure 45. Change in conductivity concentrations during July 16 2003 with distance downstream from Lake of the Prairies.

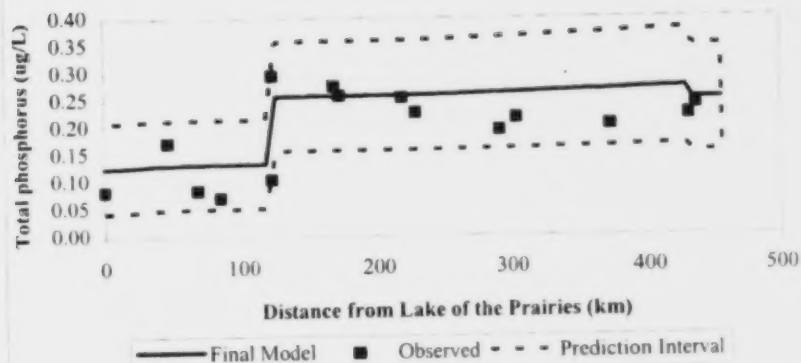


Figure 46. Change in total phosphorus concentrations during July 16 2003 with distance downstream from Lake of the Prairies.

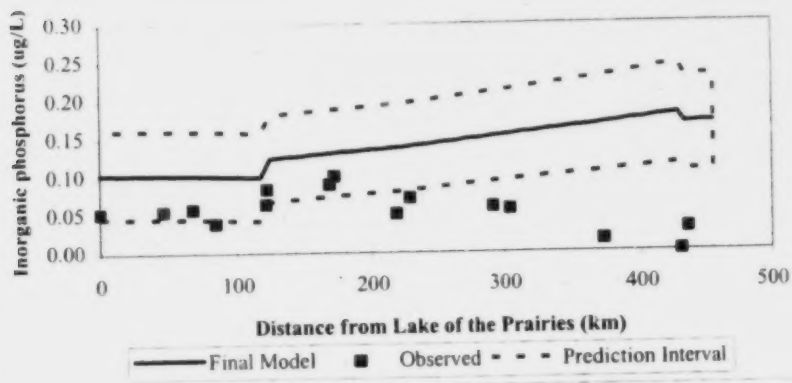


Figure 47. Change in inorganic phosphorus concentrations during July 16 2003 with distance downstream from Lake of the Prairies.

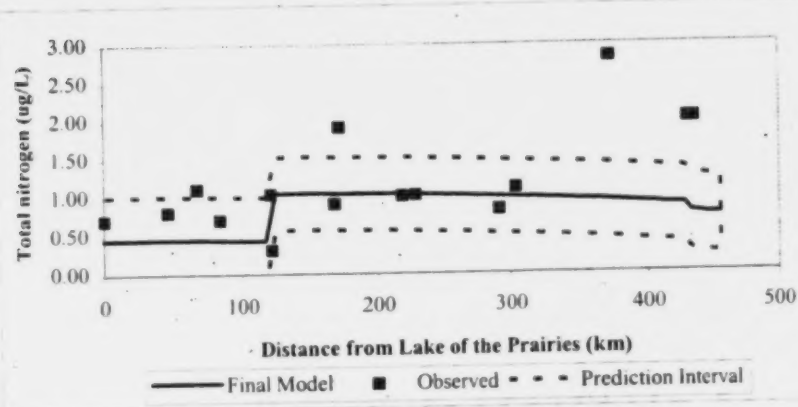


Figure 48. Change in total nitrogen concentrations during July 16 2003 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).

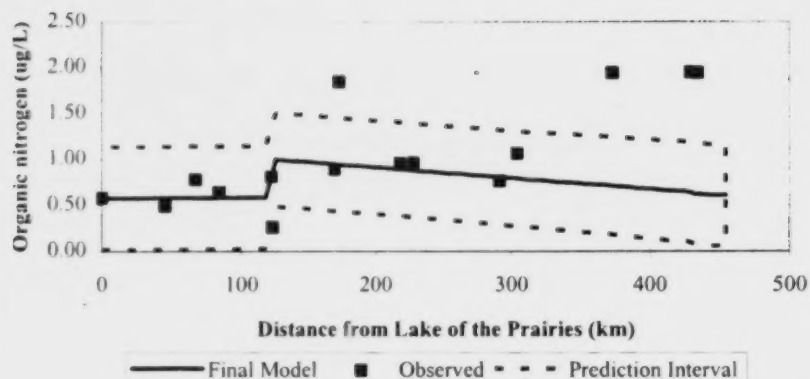


Figure 49. Change in organic nitrogen concentrations during July 16 2003 with distance downstream from Lake of the Prairies.

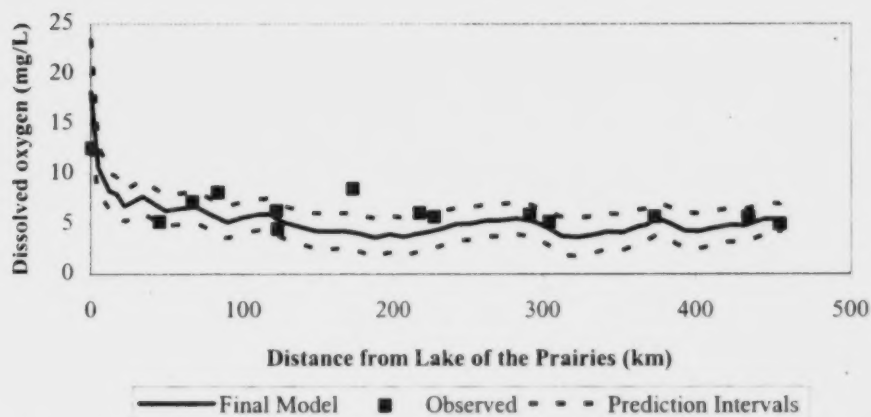


Figure 50. Change in dissolved oxygen concentrations during July 29 2003 with distance downstream from Lake of the Prairies.

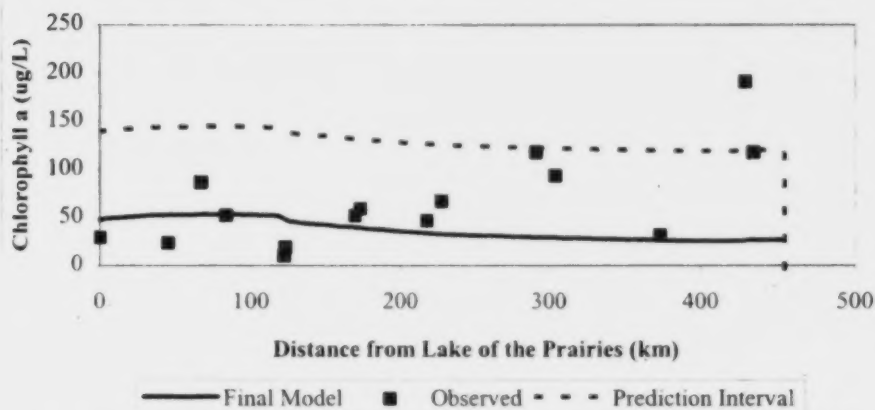


Figure 51. Change in chlorophyll a concentrations during July 29 2003 with distance , downstream from Lake of the Prairies (negative prediction intervals not shown).

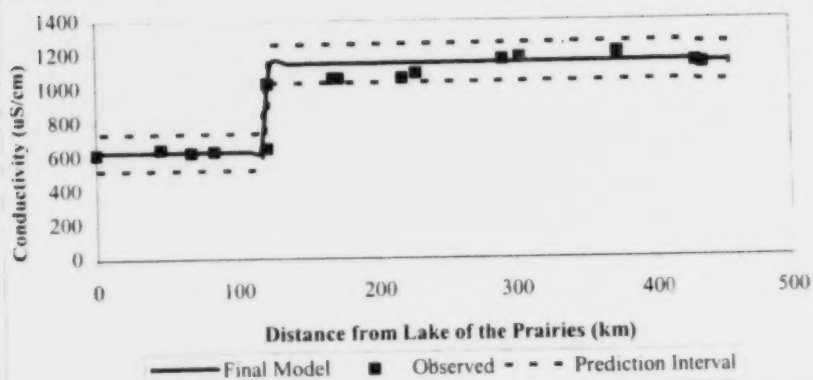


Figure 52. Change in conductivity concentrations during July 29 2003 with distance downstream from Lake of the Prairies.

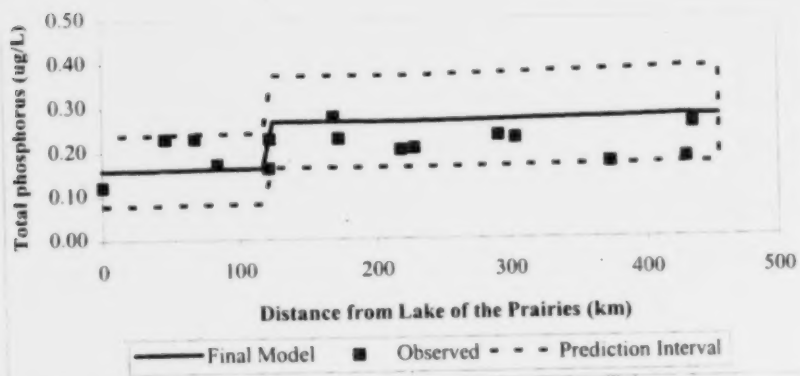


Figure 53. Change in total phosphorus concentrations during July 29 2003 with distance downstream from Lake of the Prairies.

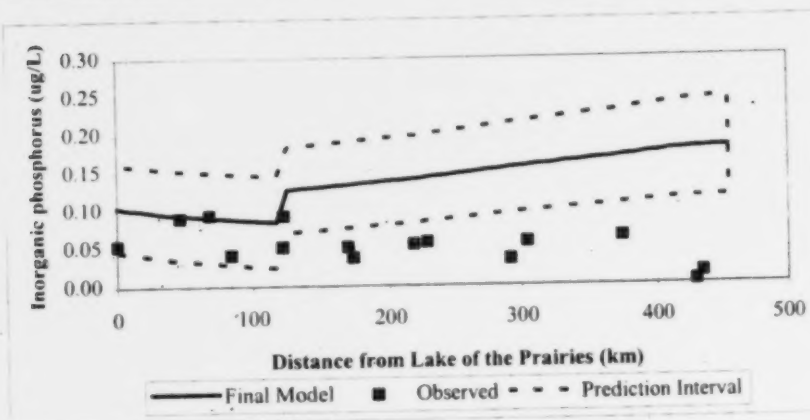


Figure 54. Change in inorganic phosphorus concentrations during July 29 2003 with distance downstream from Lake of the Prairies.

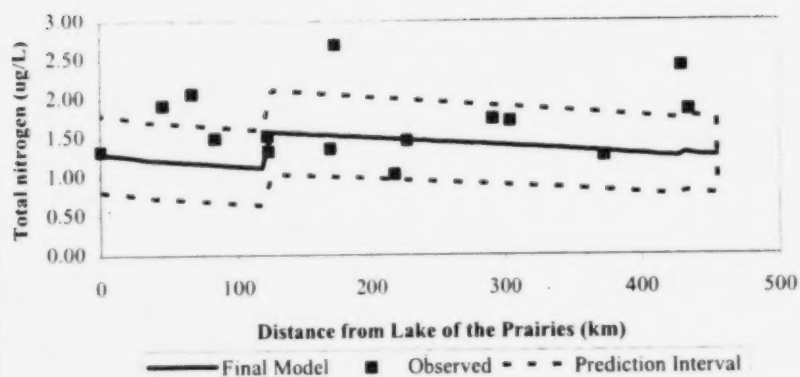


Figure 55. Change in total nitrogen concentrations during July 29 2003 with distance downstream from Lake of the Prairies.

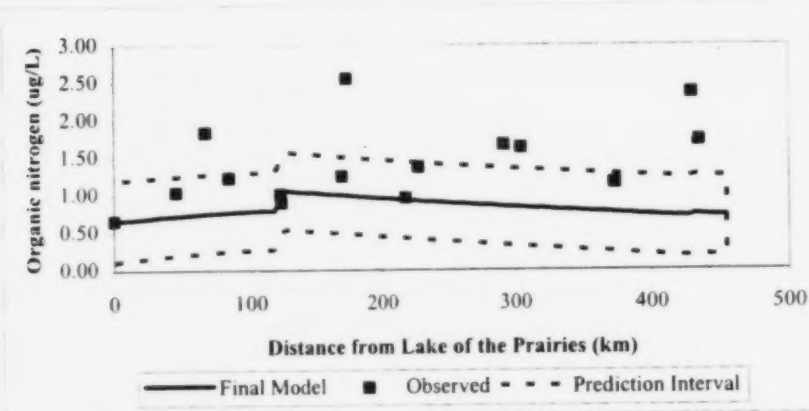


Figure 56. Change in organic nitrogen concentrations during July 29 2003 with distance downstream from Lake of the Prairies.

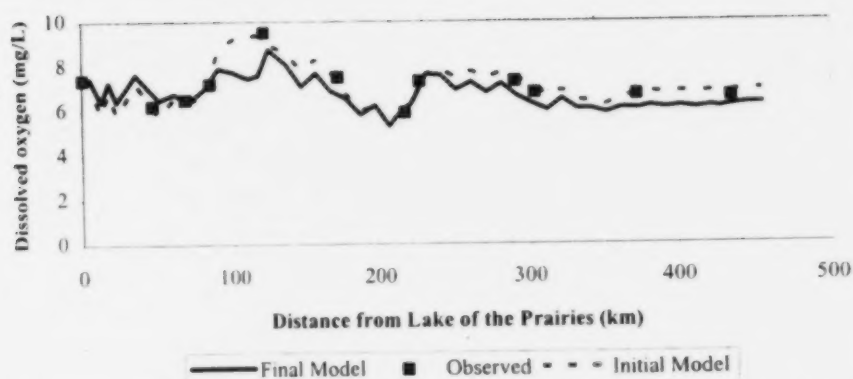


Figure 57. Change in dissolved oxygen concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

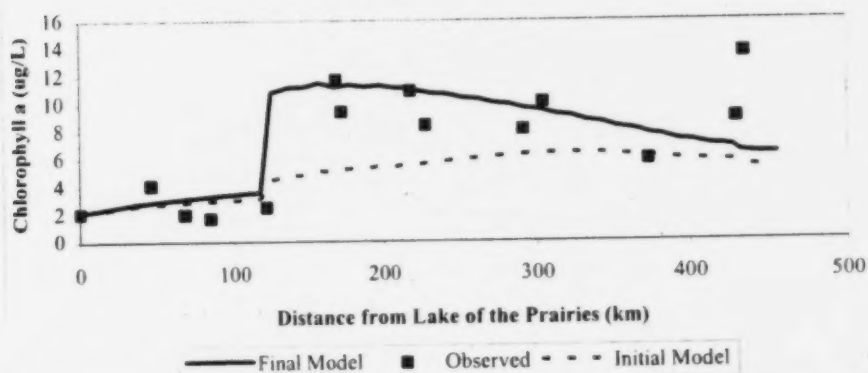


Figure 58. Change in chlorophyll a concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

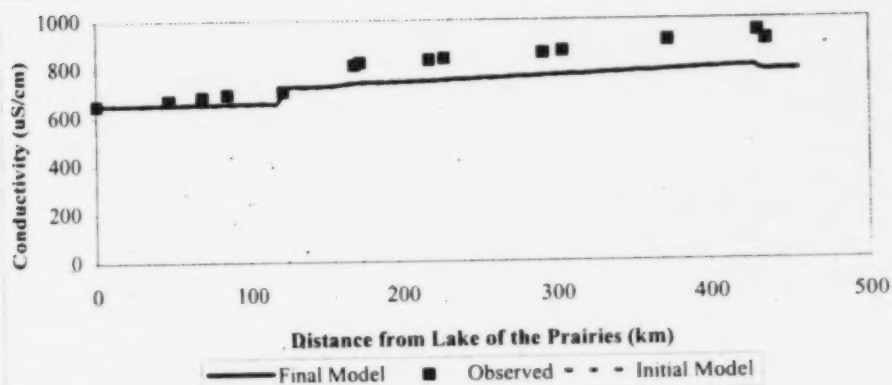


Figure 59. Change in conductivity concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

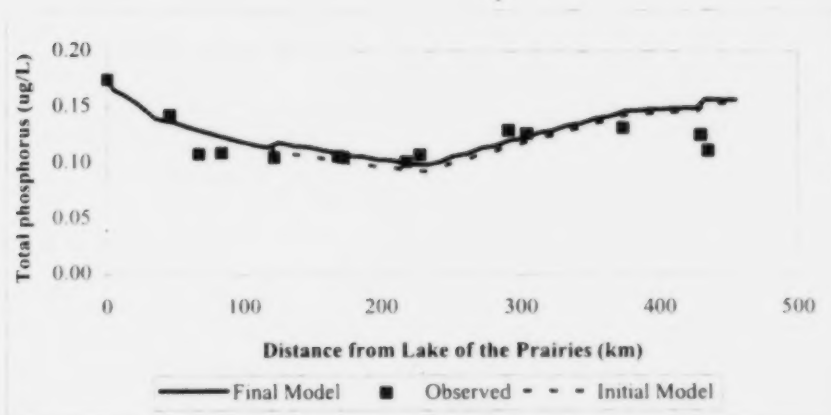


Figure 60. Change in total phosphorus concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

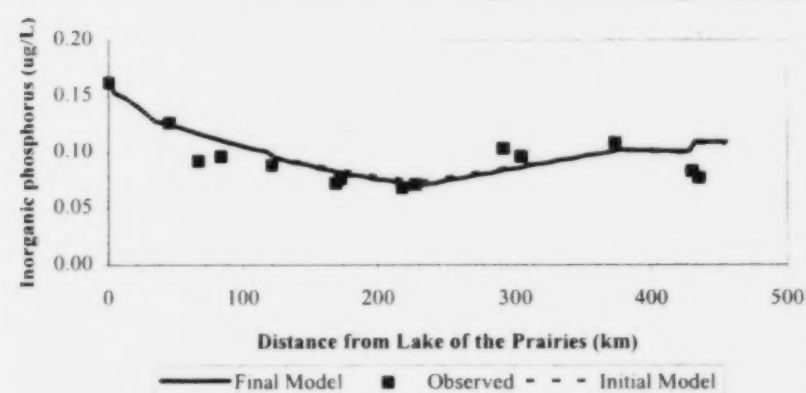


Figure 61. Change in inorganic phosphorus concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

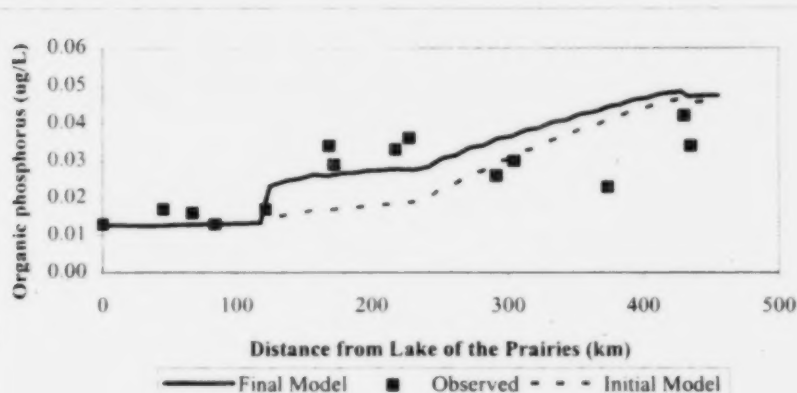


Figure 62. Change in organic phosphorus concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

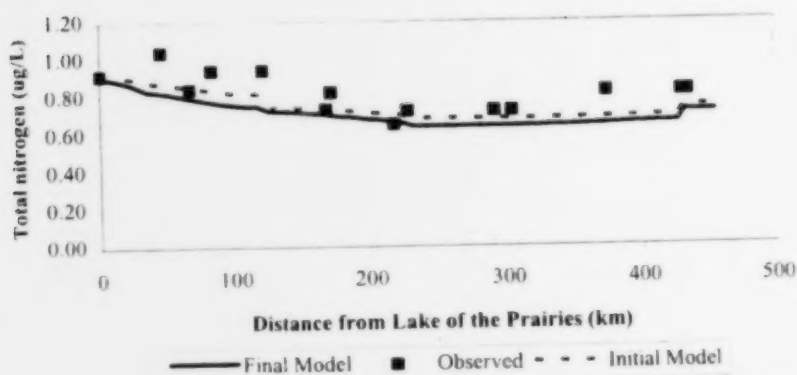


Figure 63. Change in total nitrogen concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

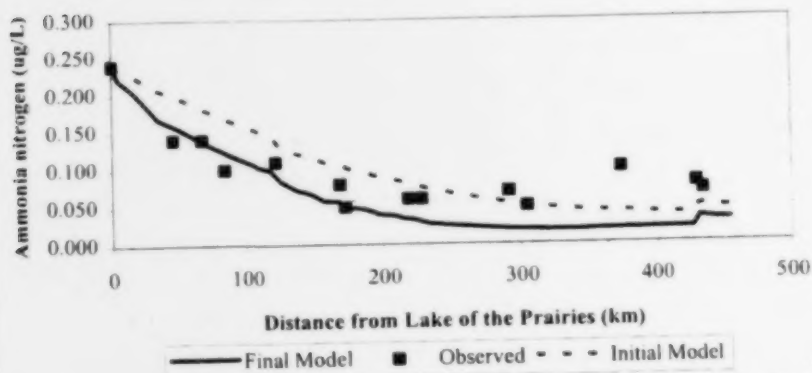


Figure 64. Change in ammonia concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

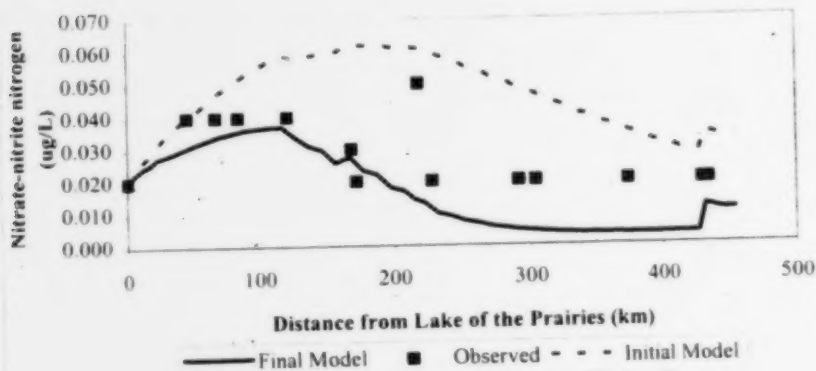


Figure 65. Change in nitrite-nitrate concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

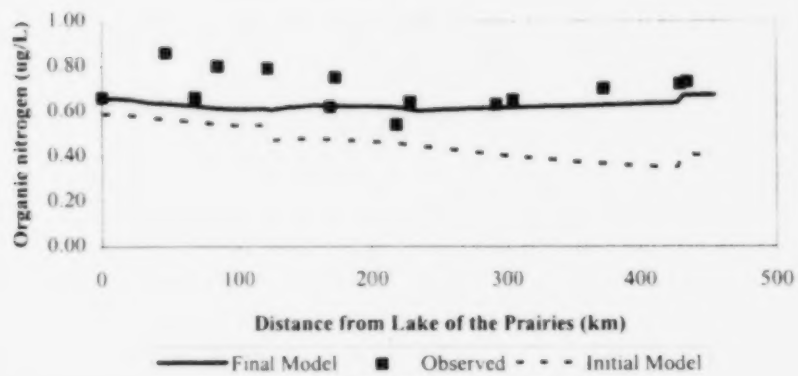


Figure 66. Change in organic nitrogen concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

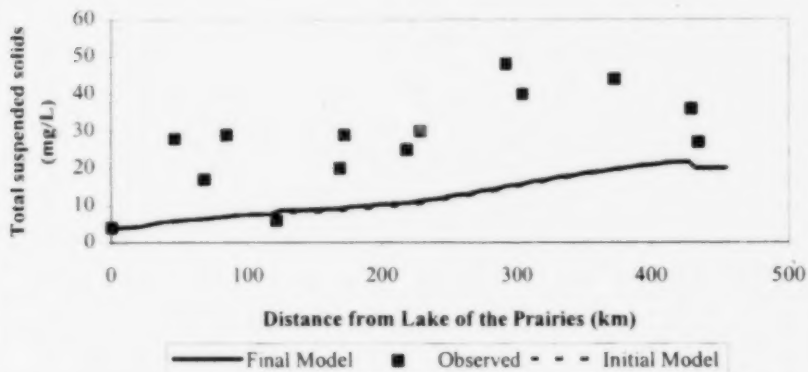


Figure 67. Change in total suspended solids concentrations during September 19 2001 with distance downstream from Lake of the Prairies.

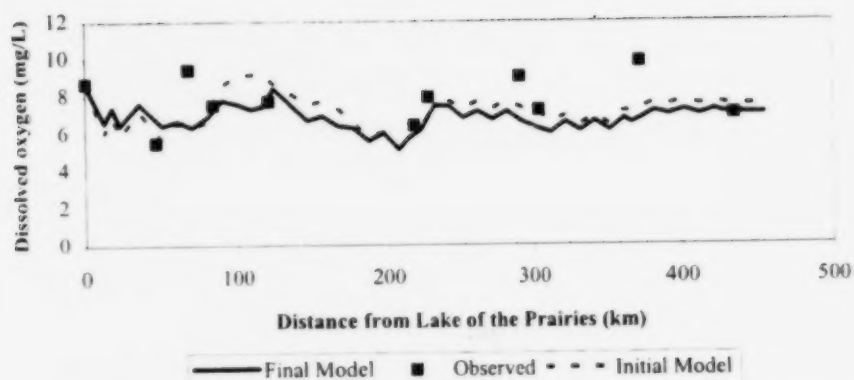


Figure 68. Change in dissolved oxygen concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

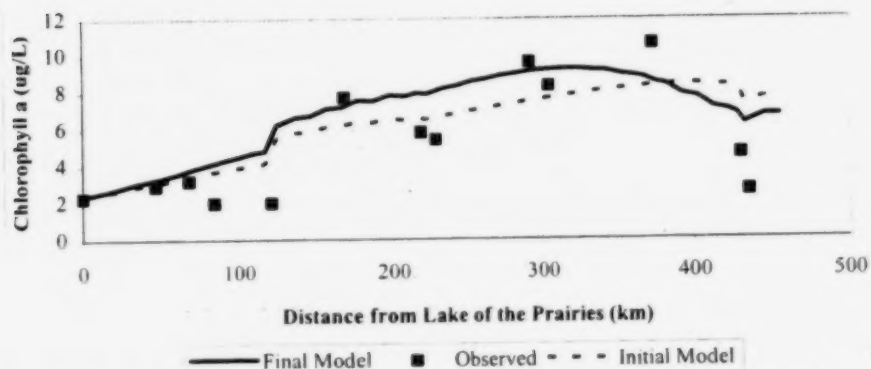


Figure 69. Change in chlorophyll a concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

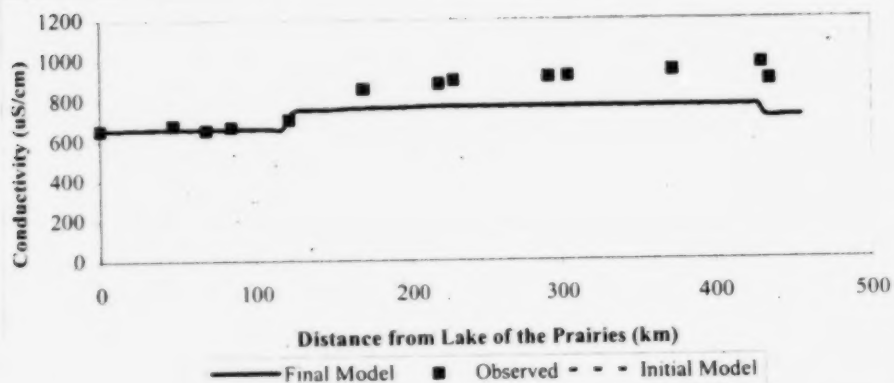


Figure 70. Change in conductivity concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

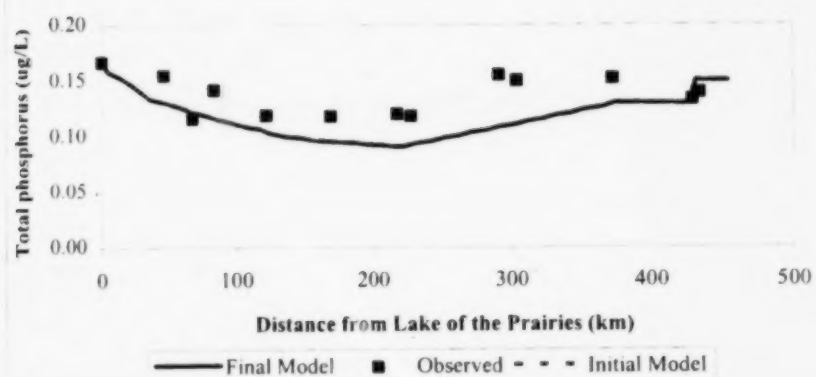


Figure 71. Change in total phosphorus concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

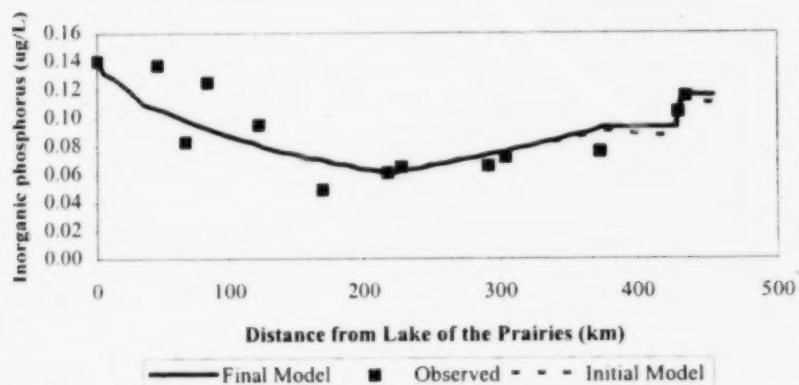


Figure 72. Change in inorganic phosphorus concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

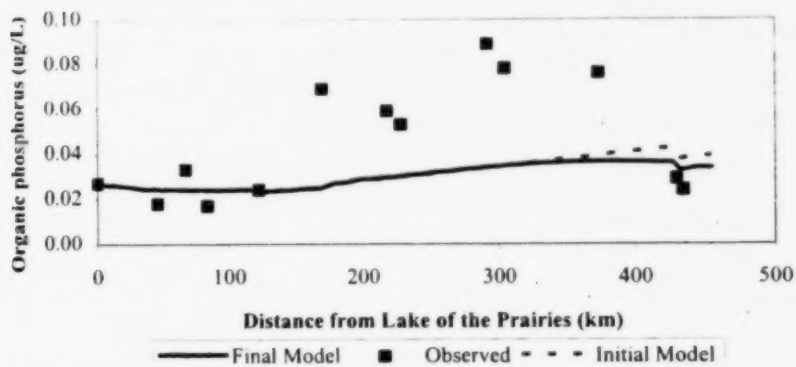


Figure 73. Change in organic phosphorus concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

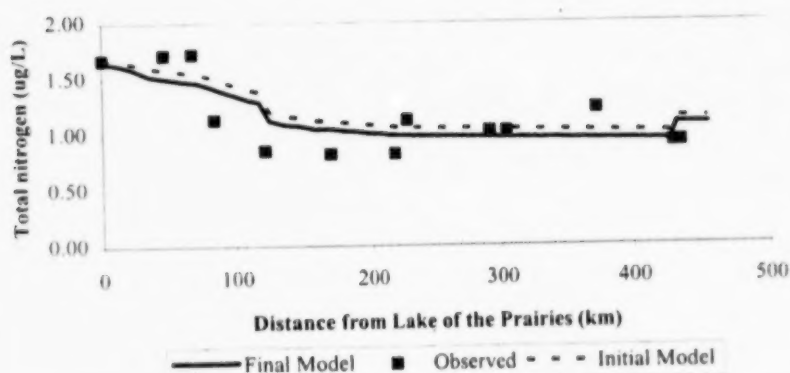


Figure 74. Change in total nitrogen concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

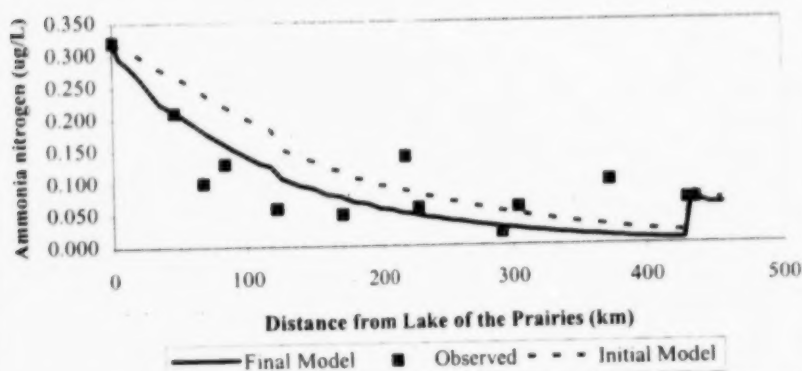


Figure 75. Change in ammonia concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

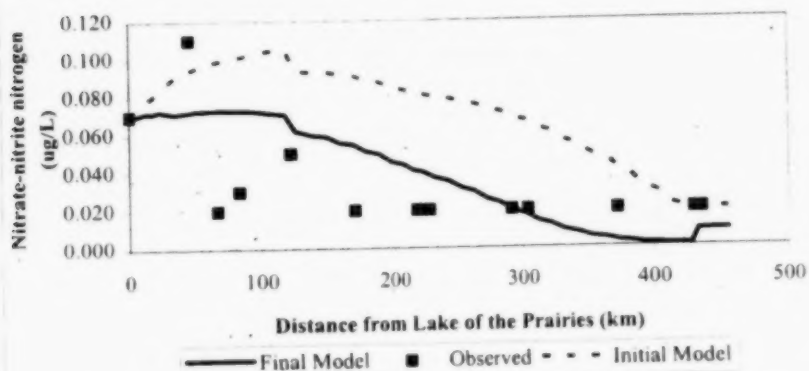


Figure 76. Change in nitrite-nitrate concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

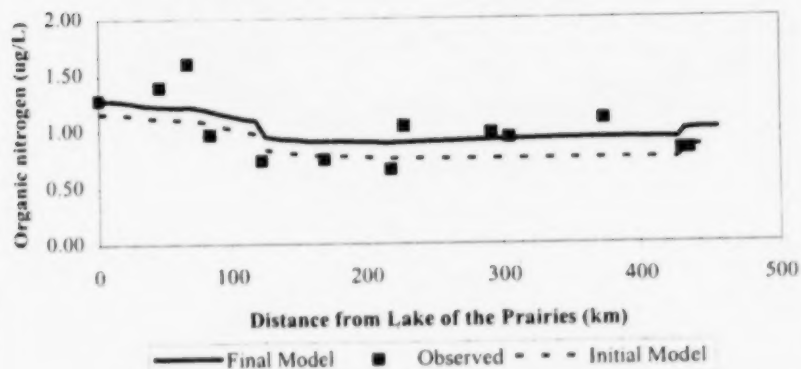


Figure 77. Change in organic nitrogen concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

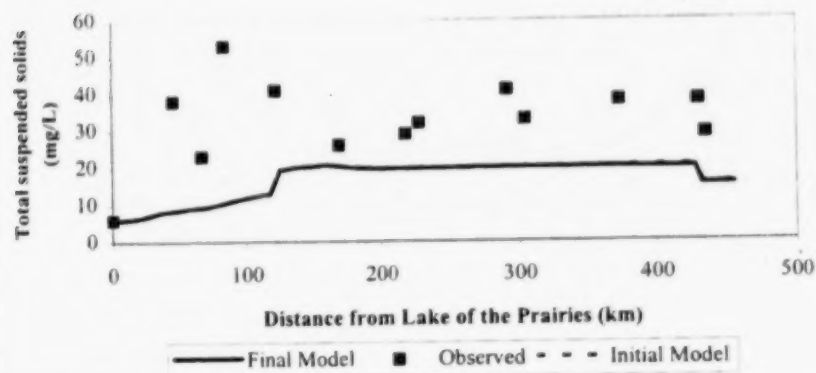


Figure 78. Change in total suspended solids concentrations during September 4 2001 with distance downstream from Lake of the Prairies.

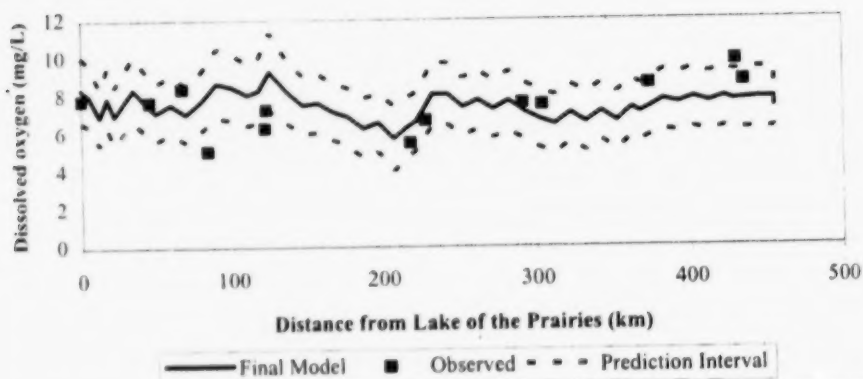


Figure 79. Change in dissolved oxygen concentrations during September 4 2002 with distance downstream from Lake of the Prairies.

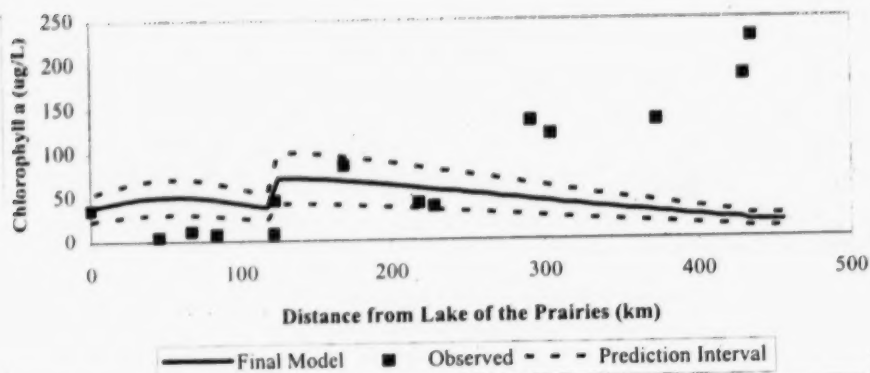


Figure 80. Change in chlorophyll a concentrations during September 4 2002 with distance downstream from Lake of the Prairies.

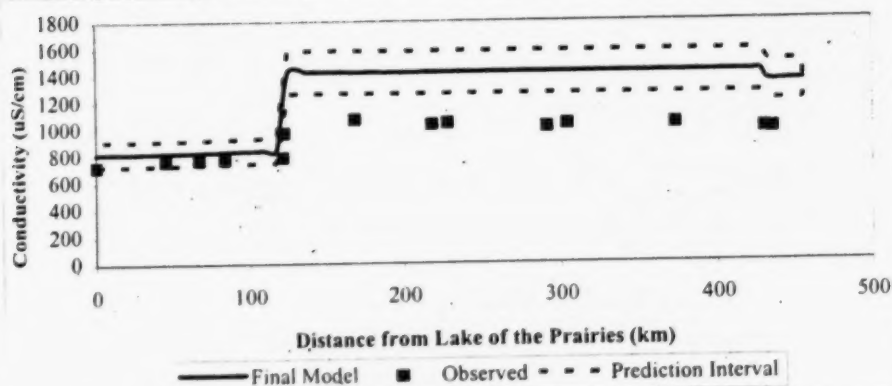


Figure 81. Change in conductivity concentrations during September 4 2002 with distance downstream from Lake of the Prairies.

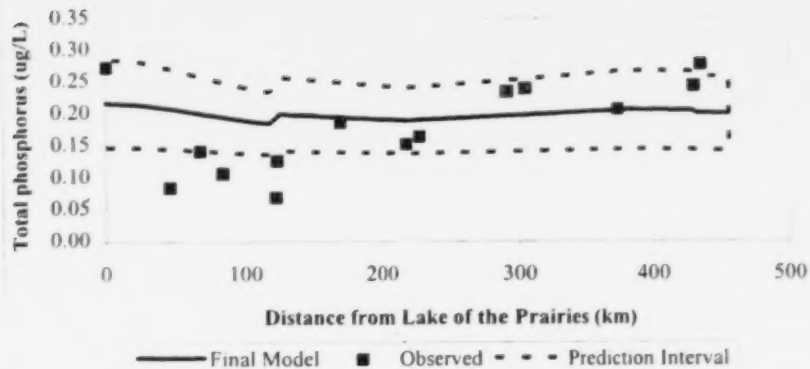


Figure 82. Change in total phosphorus concentrations during September 4 2002 with distance downstream from Lake of the Prairies.

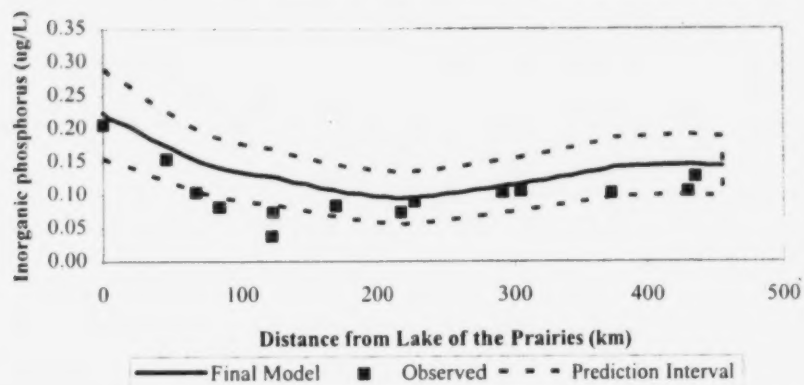


Figure 83. Change in inorganic phosphorus concentrations during September 4 2002 with distance downstream from Lake of the Prairies.

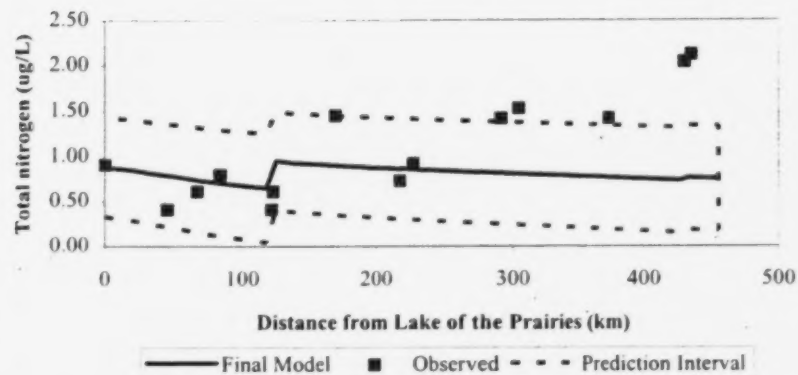


Figure 84. Change in total nitrogen concentrations during September 4 2002 with distance downstream from Lake of the Prairies.

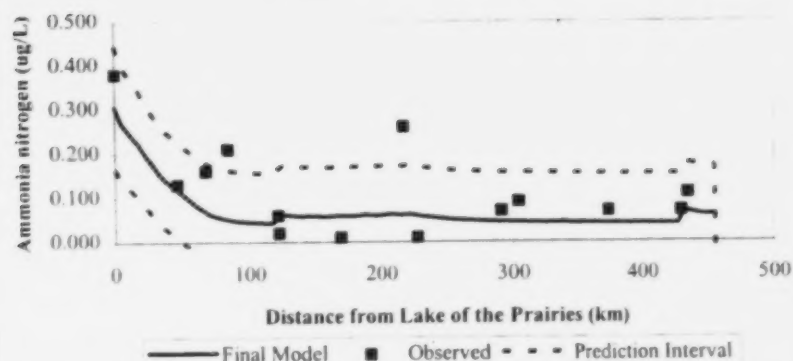


Figure 85. Change in ammonia concentrations during September 4 2002 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).

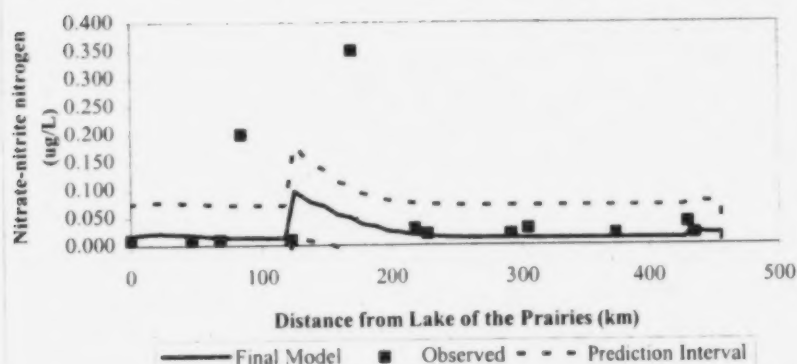


Figure 86. Change in nitrite-nitrate concentrations during September 4 2002 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).

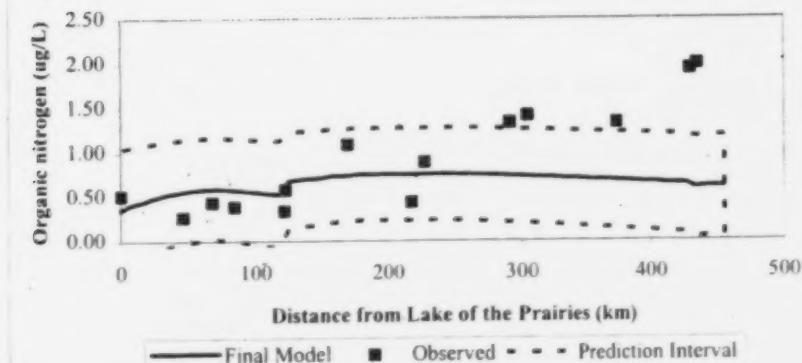


Figure 87. Change in organic nitrogen concentrations during September 4 2002 with downstream from Lake of the Prairies (negative prediction intervals not shown).

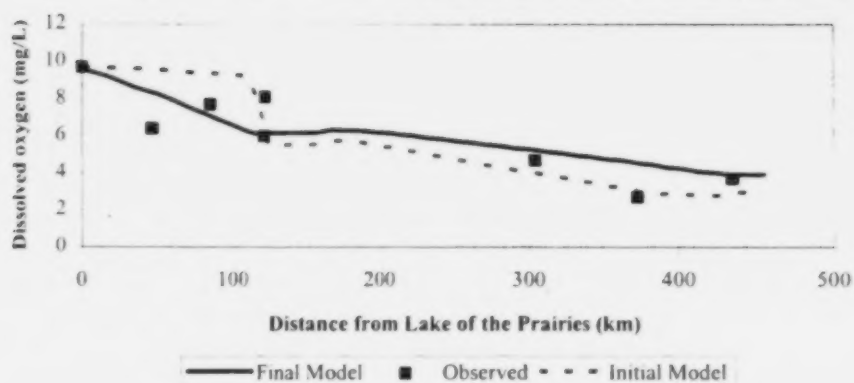


Figure 88 Change in dissolved oxygen concentrations during January 2002 with distance downstream from Lake of the Prairies.

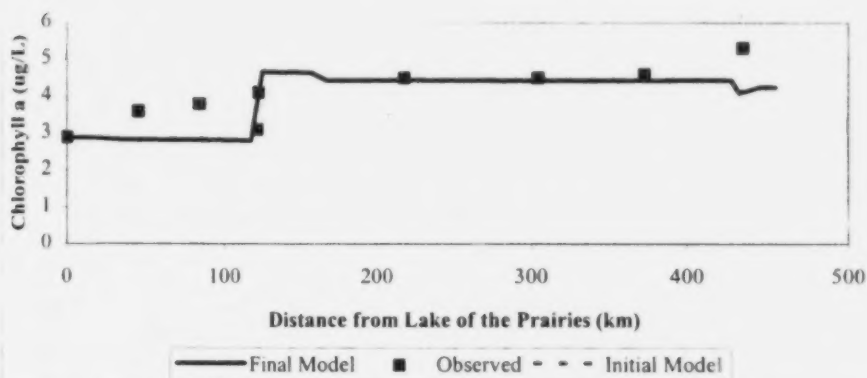


Figure 89. Change in chlorophyll a concentrations during January 2002 with distance downstream from Lake of the Prairies.

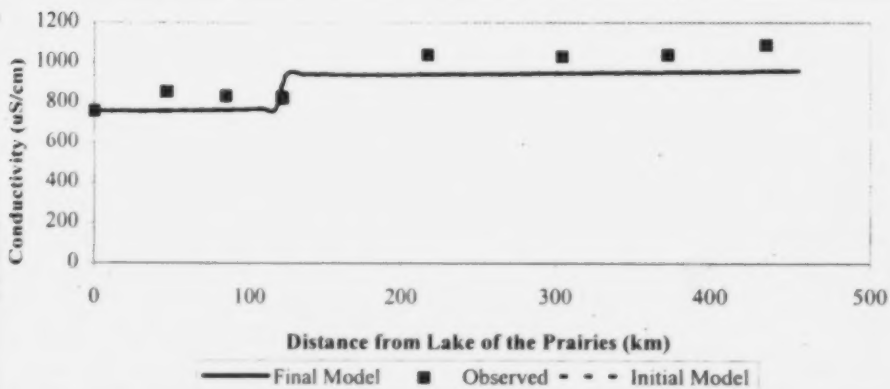


Figure 90. Change in conductivity concentrations during January 2002 with distance downstream from Lake of the Prairies.

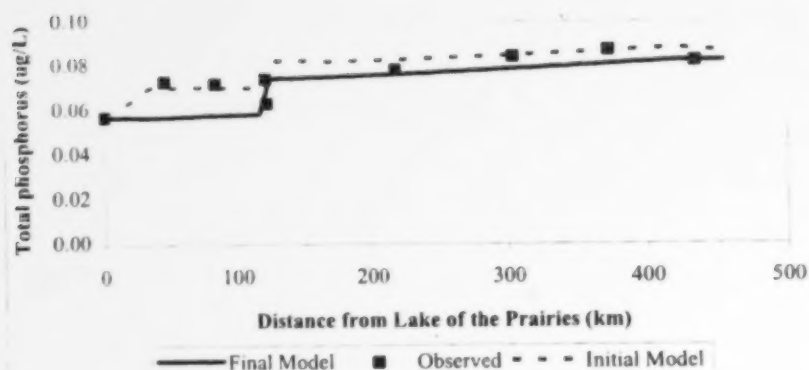


Figure 91. Change in total phosphorus concentrations during January 2002 with distance downstream from Lake of the Prairies.

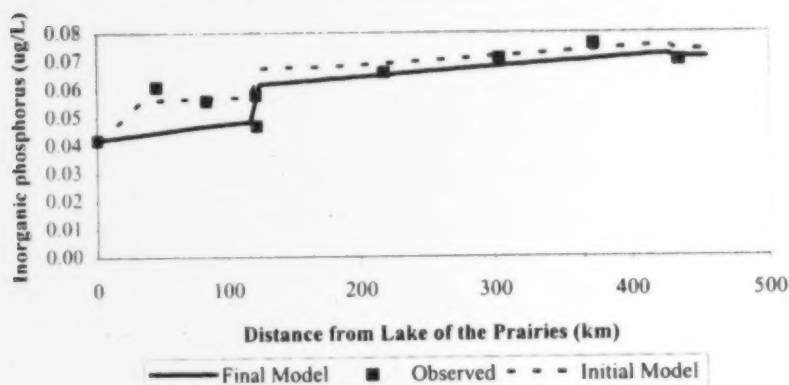


Figure 92. Change in inorganic phosphorus concentrations during January 2002 with distance downstream from Lake of the Prairies.

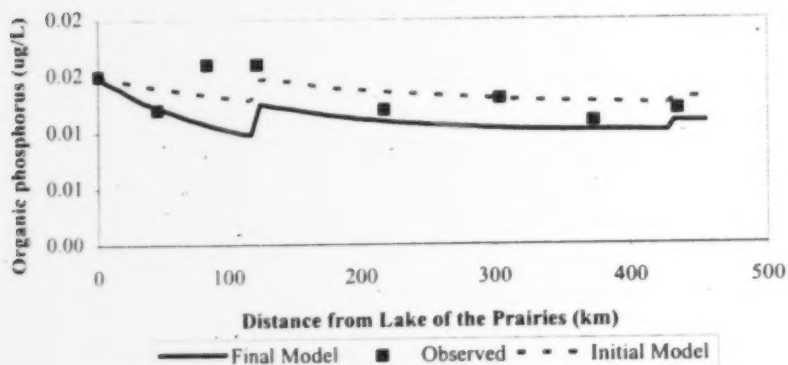


Figure 93. Change in organic phosphorus concentrations during January 2002 with distance downstream from Lake of the Prairies.

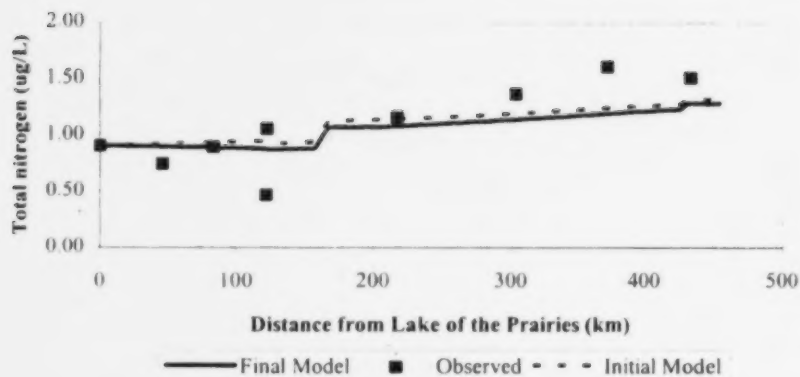


Figure 94. Change in total nitrogen concentrations during January 2002 with distance downstream from Lake of the Prairies.

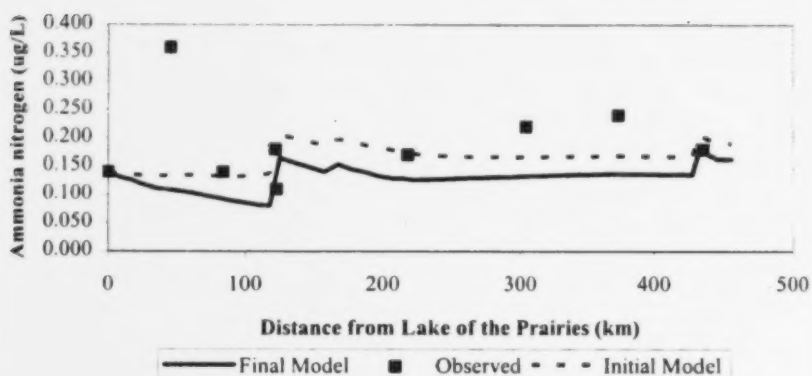


Figure 95. Change in ammonia concentrations during January 2002 with distance downstream from Lake of the Prairies.

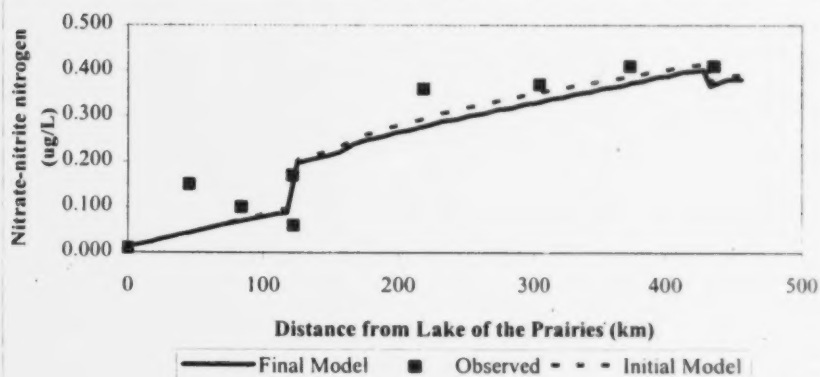


Figure 96. Change in nitrite-nitrate concentrations during January 2002 with distance downstream from Lake of the Prairies.

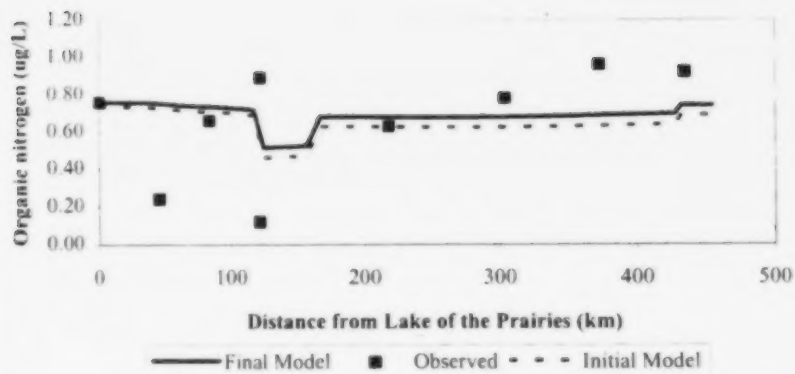


Figure 97. Change in organic nitrogen concentrations during January 2002 with distance downstream from Lake of the Prairies.

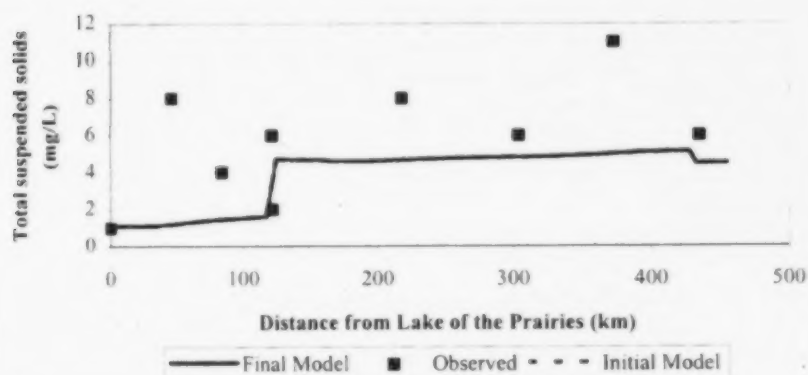


Figure 98. Change in total suspended solids concentrations during January 2002 with distance downstream from Lake of the Prairies.

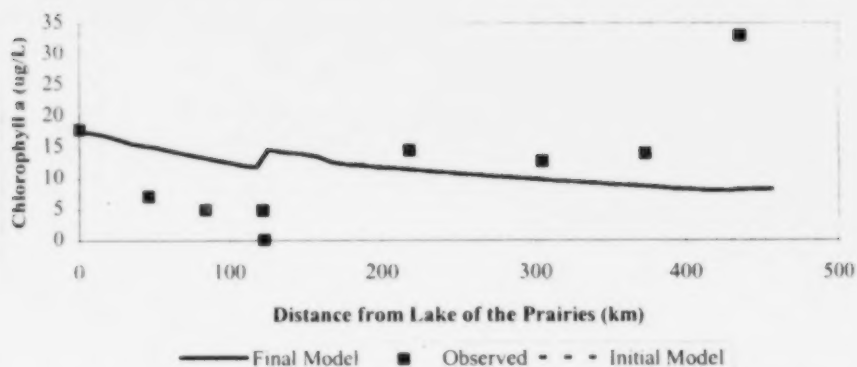


Figure 99. Change in chlorophyll a concentrations during December 2001 with distance downstream from Lake of the Prairies.

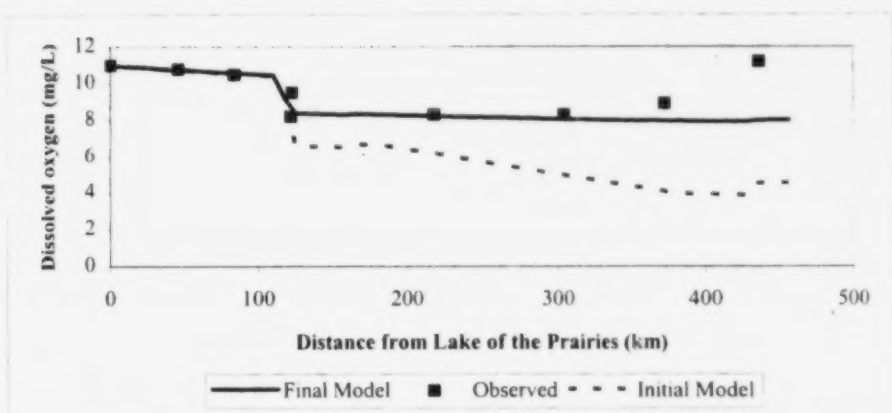


Figure 100. Change in dissolved oxygen concentrations during December 2001 with distance downstream from Lake of the Prairies.

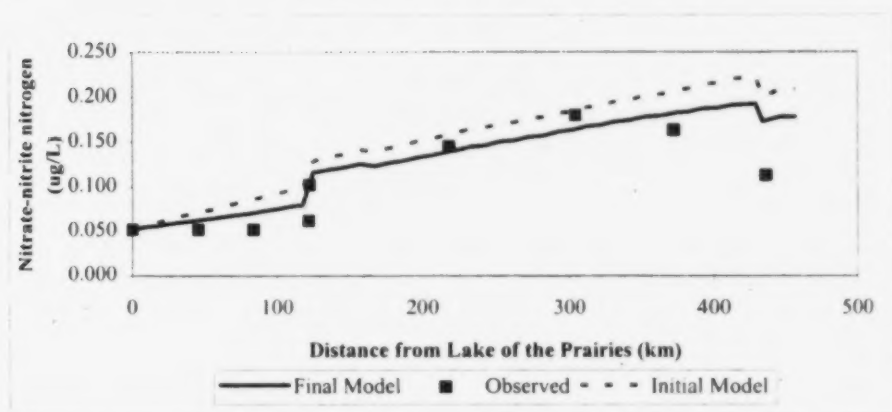


Figure 101. Change in nitrite-nitrate concentrations during December 2001 with distance downstream from Lake of the Prairies.

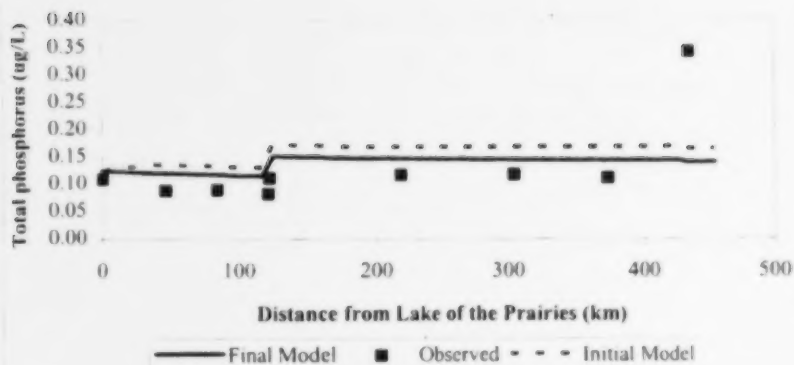


Figure 102. Change in total phosphorus concentrations during December 2002 with distance downstream from Lake of the Prairies.

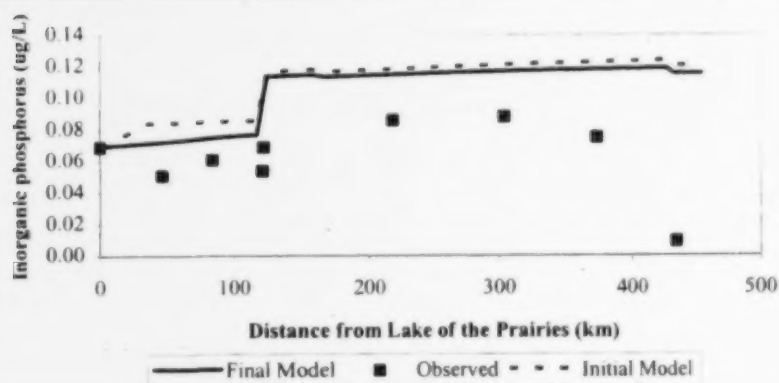


Figure 103. Change in inorganic phosphorus concentrations during December 2002 with distance downstream from Lake of the Prairies.

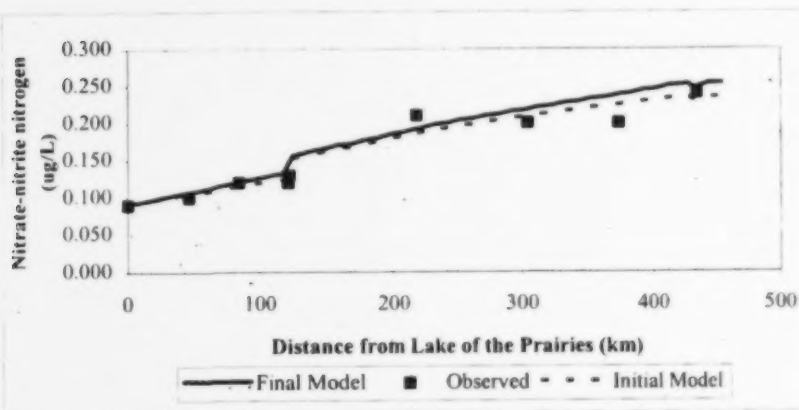


Figure 104. Change in nitrite-nitrate concentrations during December 2002 with distance downstream from Lake of the Prairies.

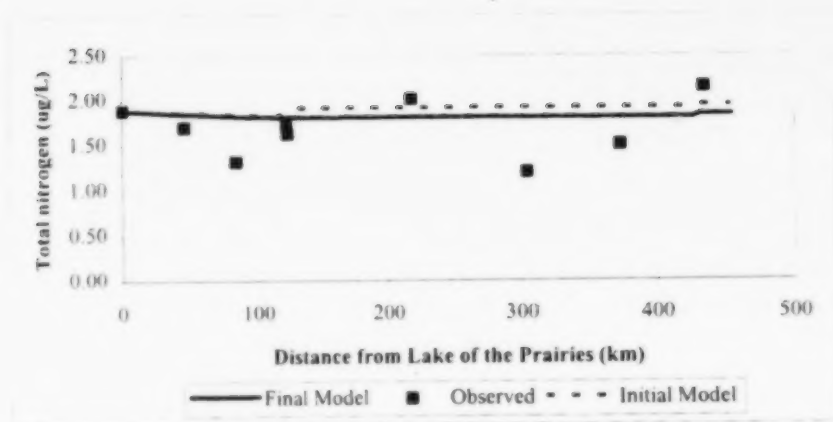


Figure 105. Change in total nitrogen concentrations during December 2002 with distance downstream from Lake of the Prairies.

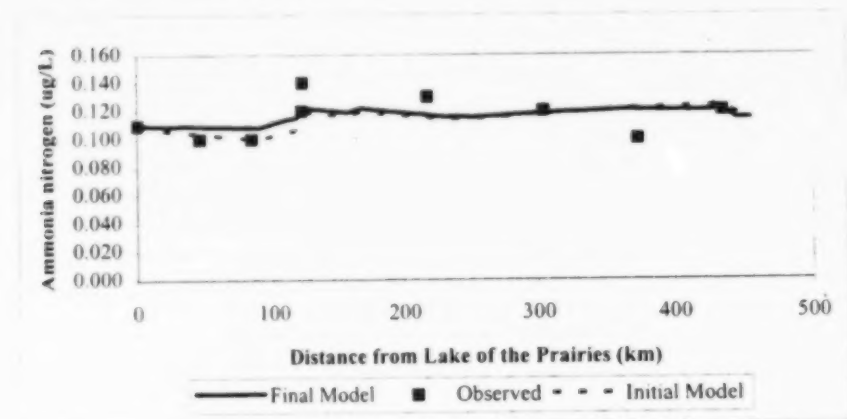


Figure 106. Change in ammonia concentrations during December 2002 with distance downstream from Lake of the Prairies.

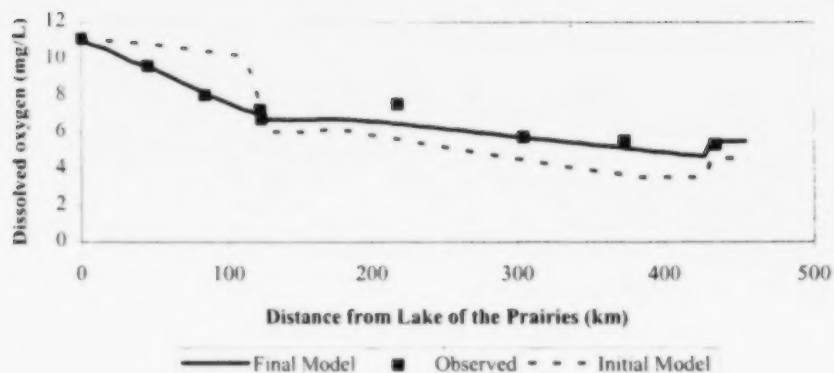


Figure 107. Change in dissolved oxygen concentrations during February 2002 with distance downstream from Lake of the Prairies.

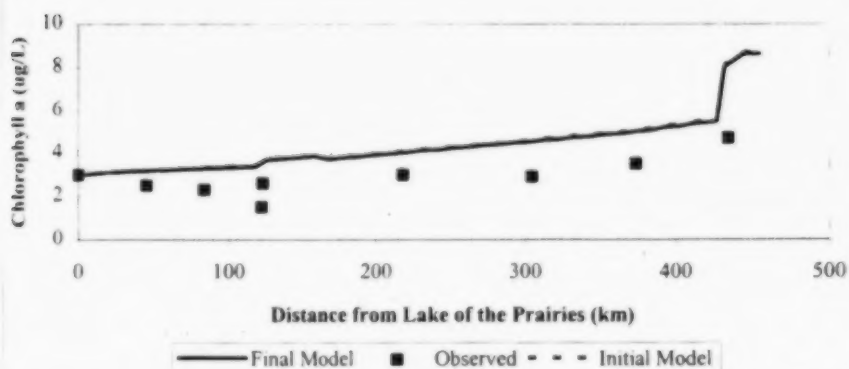


Figure 108. Change in chlorophyll a concentrations during February 2002 with distance downstream from Lake of the Prairies.

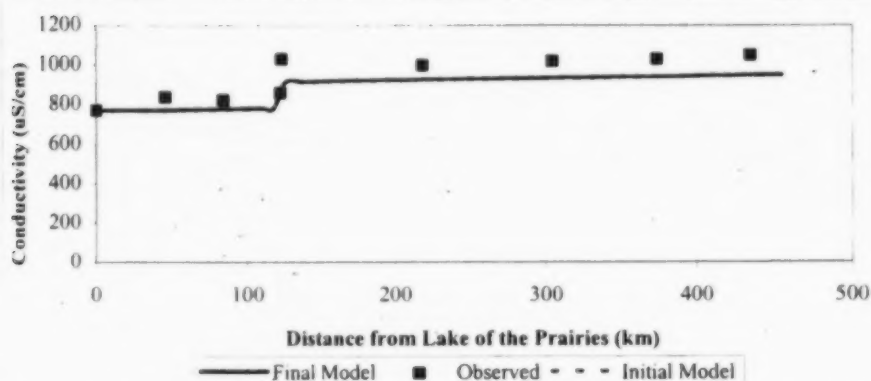


Figure 109. Change in conductivity concentrations during February 2002 with distance downstream from Lake of the Prairies.

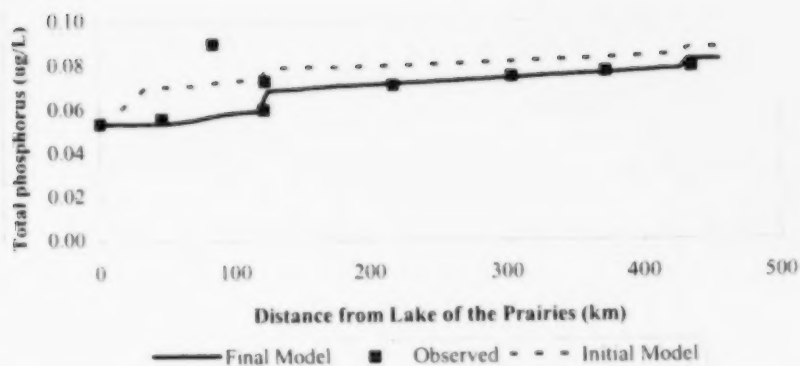


Figure 110. Change in total phosphorus concentrations during February 2002 with distance downstream from Lake of the Prairies.

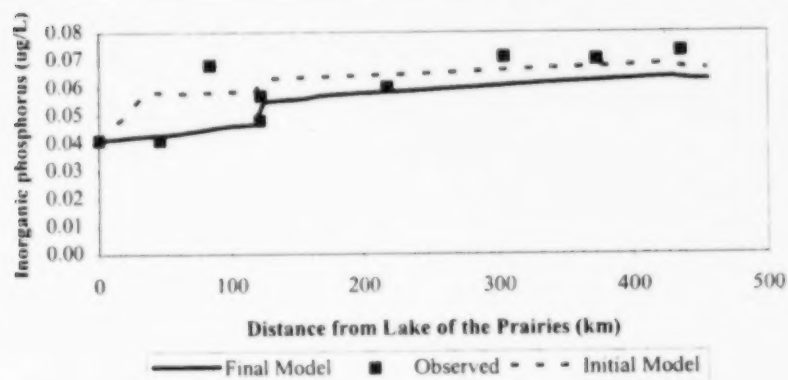


Figure 111. Change in inorganic phosphorus concentrations during February 2002 with distance downstream from Lake of the Prairies.

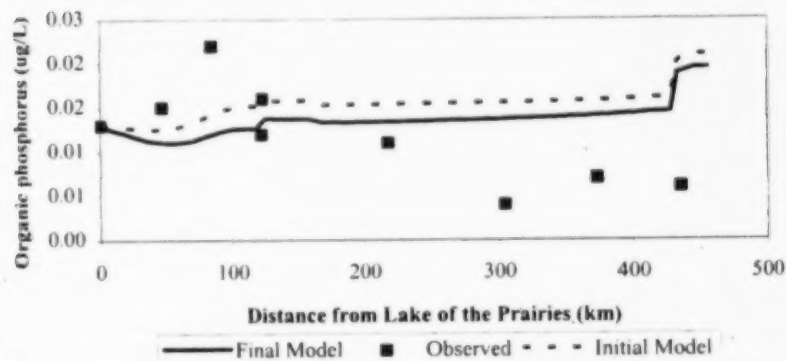


Figure 112. Change in organic phosphorus concentrations during February 2002 with distance downstream from Lake of the Prairies.

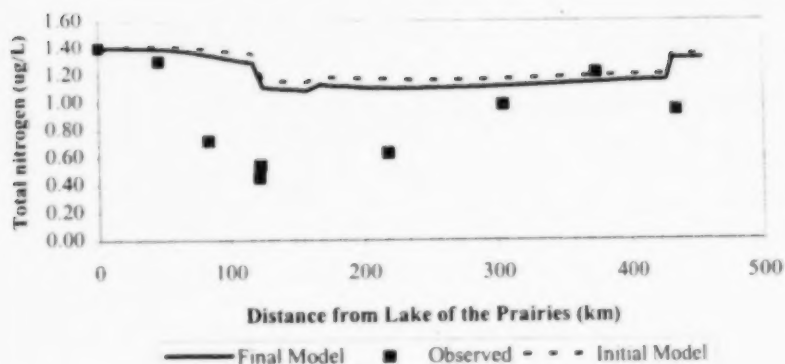


Figure 113. Change in total nitrogen concentrations during February 2002 with distance downstream from Lake of the Prairies.

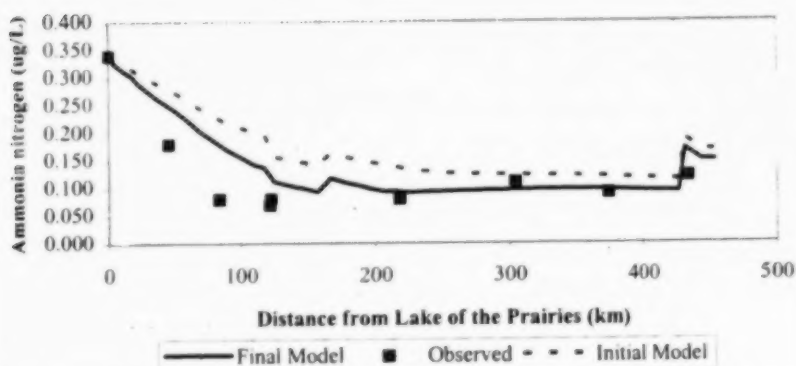


Figure 114. Change in ammonia concentrations during February 2002 with distance downstream from Lake of the Prairies.

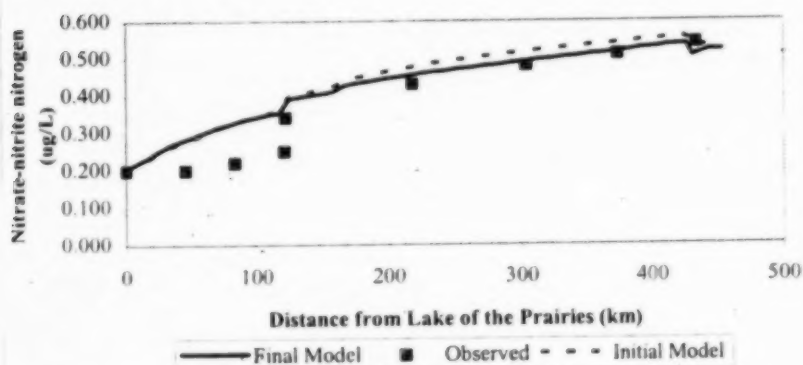


Figure 115. Change in nitrite-nitrate concentrations during February 2002 with distance downstream from Lake of the Prairies.

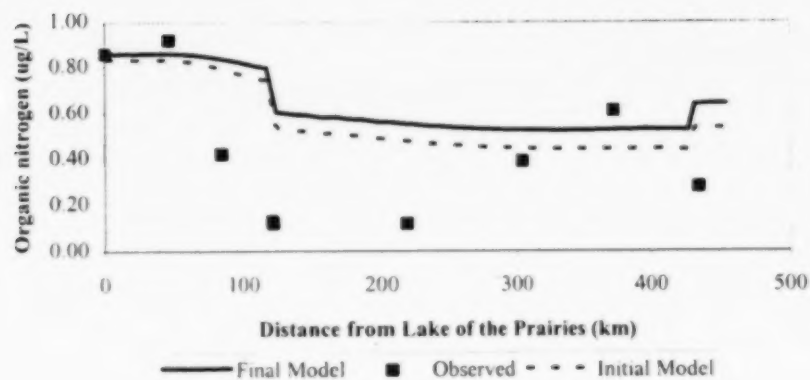


Figure 116. Change in organic nitrogen concentrations during February 2002 with distance downstream from Lake of the Prairies.

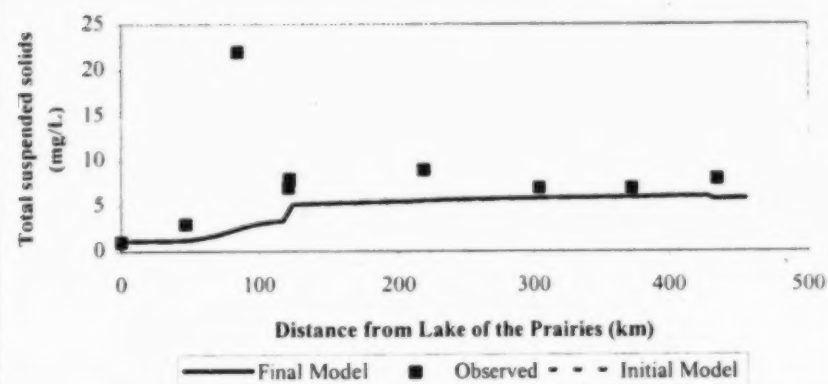


Figure 117. Change in total suspended solids concentrations during February 2002 with distance downstream from Lake of the Prairies.

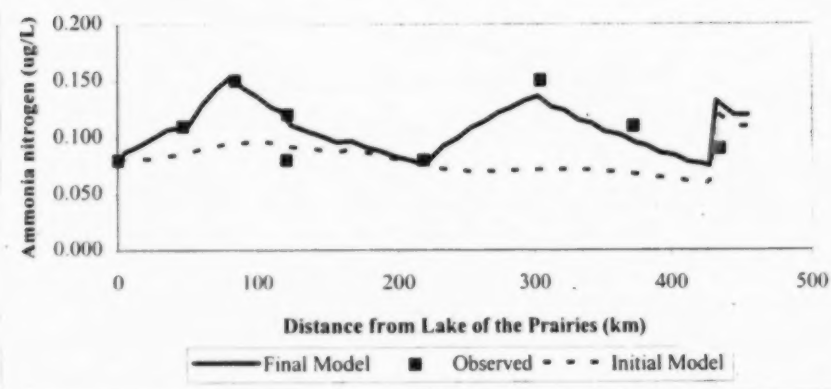


Figure 118. Change in ammonia concentrations during April 2002 with distance downstream from Lake of the Prairies.

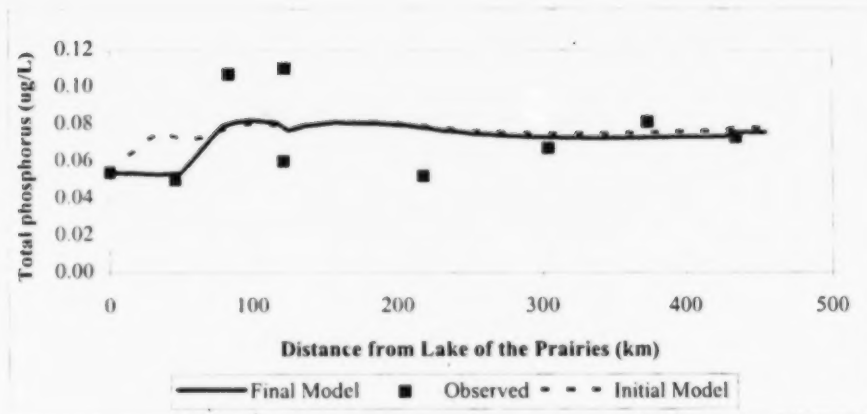


Figure 119. Change in total phosphorus concentrations during April 2002 with distance downstream from Lake of the Prairies.

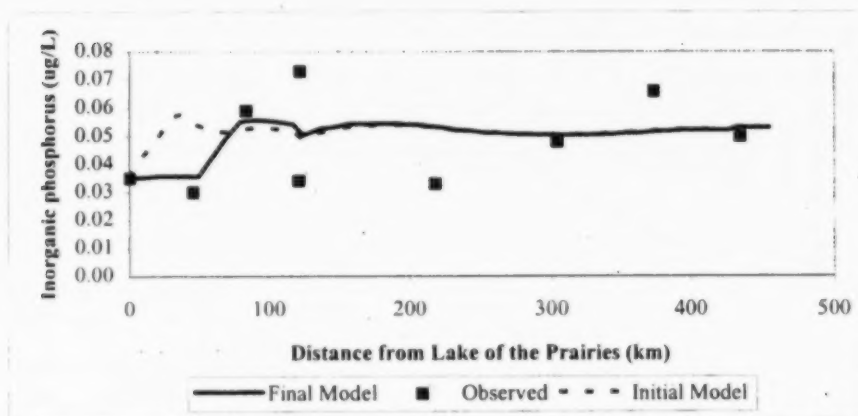


Figure 120. Change in inorganic phosphorus concentrations during April 2002 with distance downstream from Lake of the Prairies.

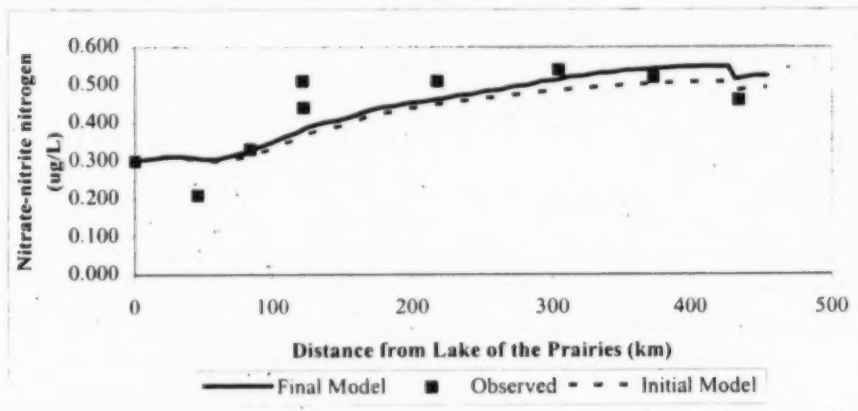


Figure 121. Change in nitrite-nitrate concentrations during April 2002 with distance downstream from Lake of the Prairies.

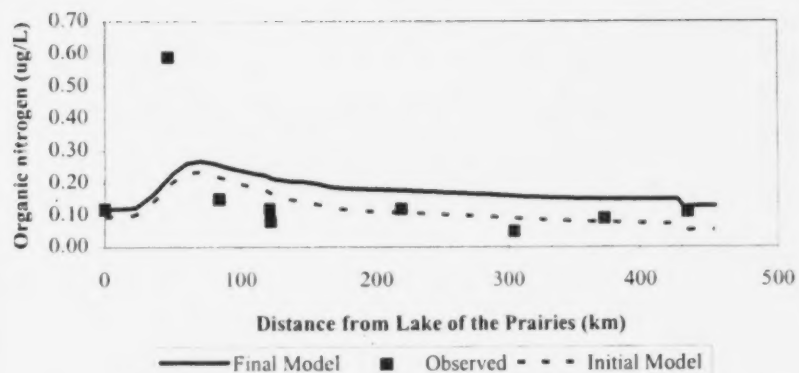


Figure 122. Change in organic nitrogen concentrations during April 2002 with distance downstream from Lake of the Prairies.

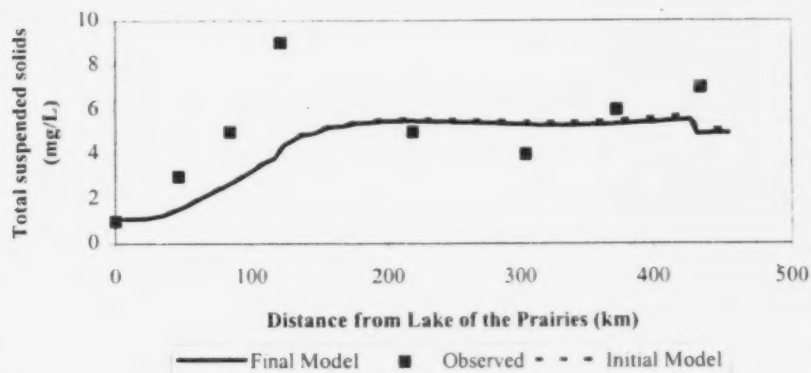


Figure 123. Change in total suspended solids concentrations during April 2002 with distance downstream from Lake of the Prairies.

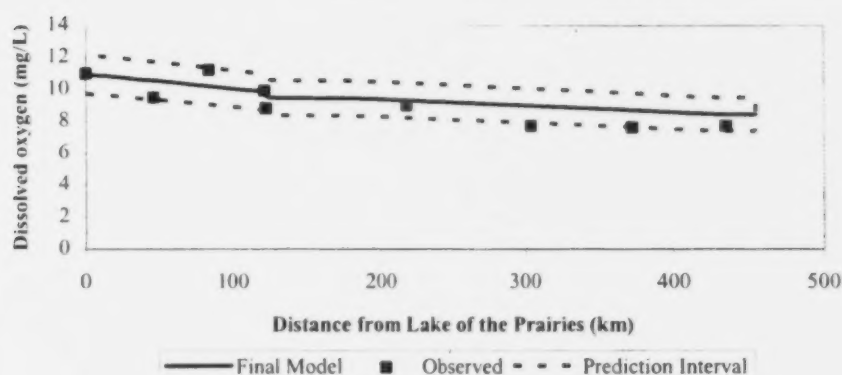


Figure 124. Change in dissolved oxygen concentrations during January 2003 with distance downstream from Lake of the Prairies.

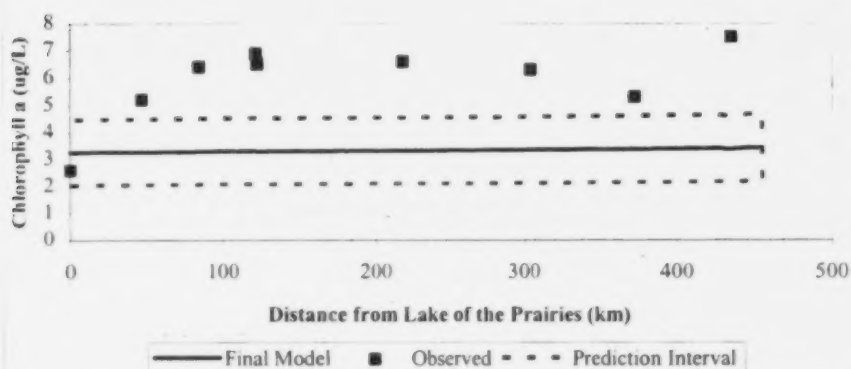


Figure 125. Change in chlorophyll a concentrations during January 2003 with distance downstream from Lake of the Prairies.

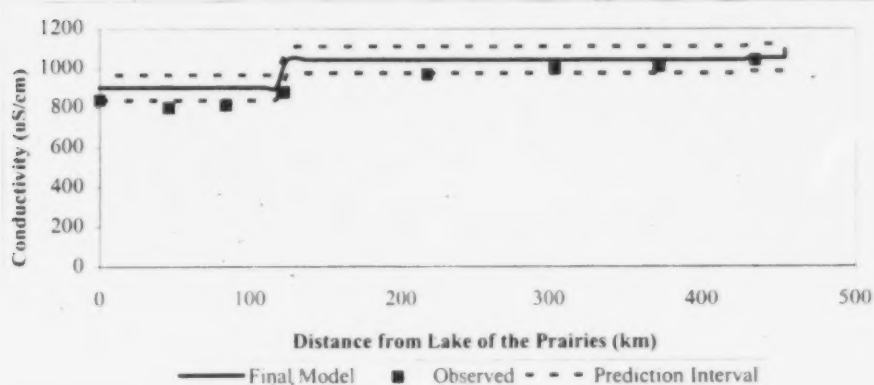


Figure 126. Change in conductivity concentrations during January 2003 with distance downstream from Lake of the Prairies.

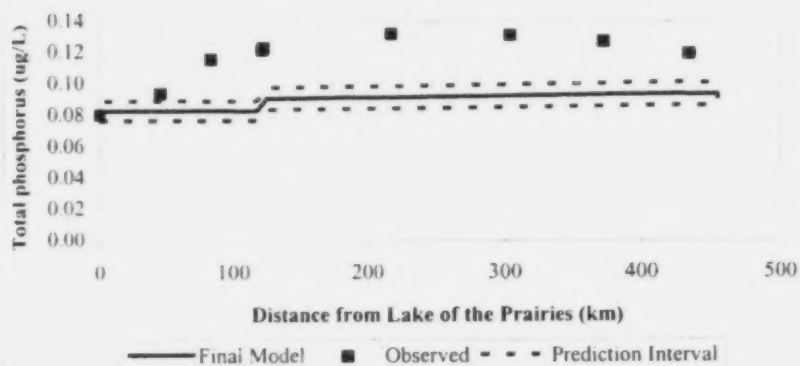


Figure 127. Change in total phosphorus concentrations during January 2003 with distance downstream from Lake of the Prairies.

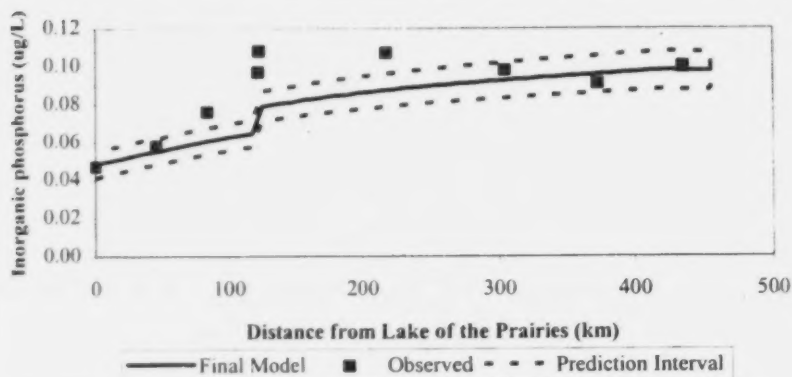


Figure 128. Change in inorganic phosphorus concentrations during January 2003 with distance downstream from Lake of the Prairies.

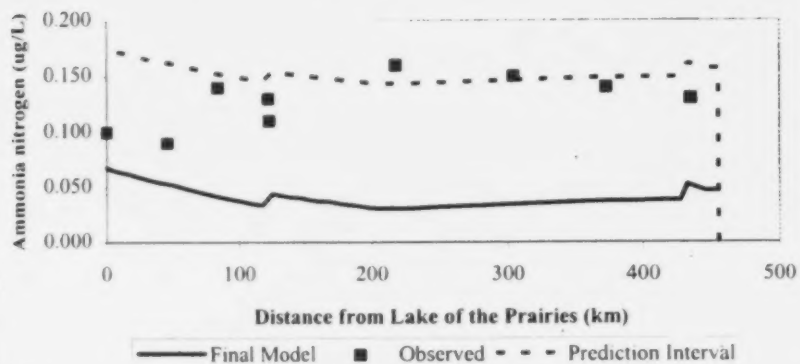


Figure 129. Change in ammonia concentrations during January 2003 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).

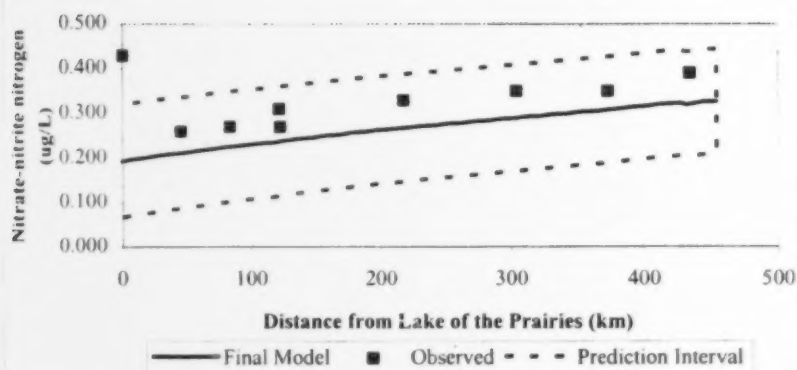


Figure 130. Change in nitrite-nitrate concentrations during January 2003 with distance downstream from Lake of the Prairies.

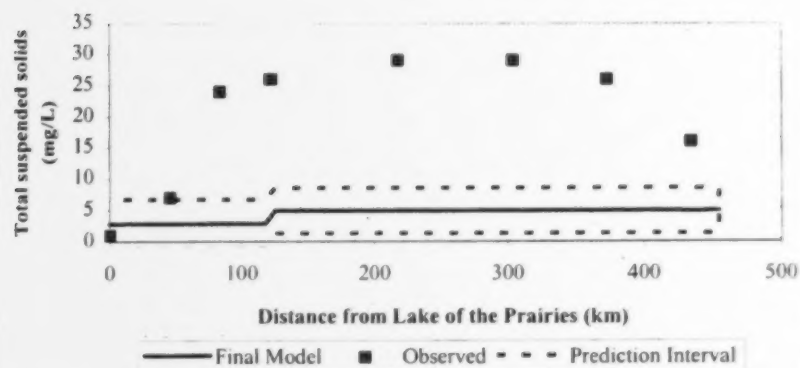


Figure 131. Change in total suspended solids concentrations during January 2003 with distance downstream from Lake of the Prairies (negative prediction intervals not shown).

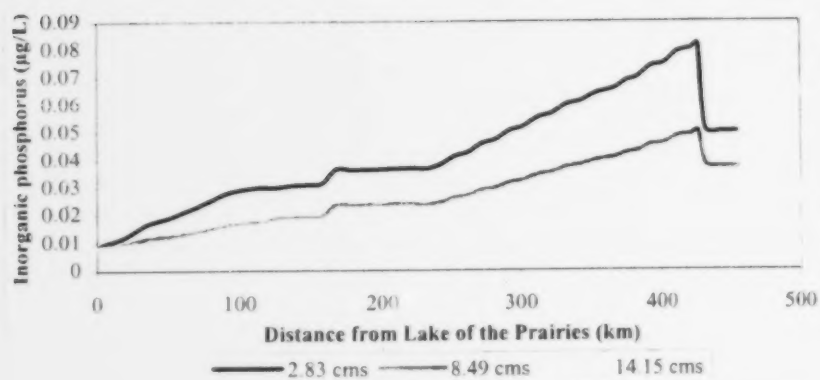


Figure 132. Change in modelled inorganic phosphorus concentrations during the spring under three outflow scenarios from Lake of the Prairies.

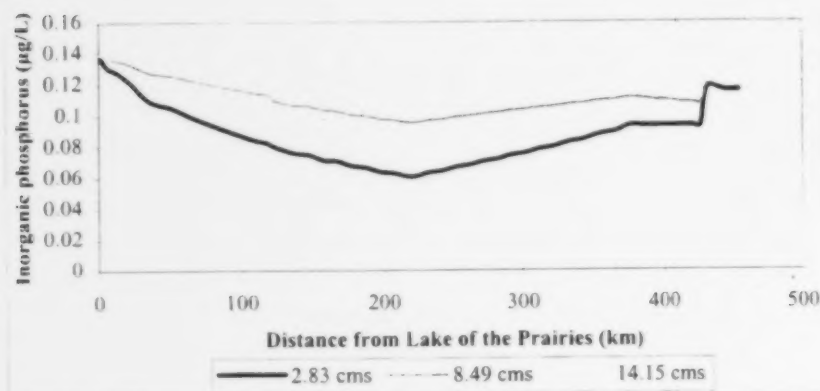


Figure 133. Change in modelled inorganic phosphorus concentrations during the fall under three outflow scenarios from Lake of the Prairies.

Table 1. Water quality station descriptions and locations on the Assiniboine River and tributaries (2001 to 2003).

Station	Location Description	Station ID #	Latitude	Longitude	Distance from Lake of the Prairies (km)
MB05MDS023	ASSINIBOINE RIVER AT OUTLET FROM SHELLMOUTH	1.0	50.9625	101.4167	0.0
MB05MES048	ASSINIBOINE RIVER NEAR RUSSELL AT CONJURING CREEK	2.0	50.8099	101.4338	46.1
MB05MES053	ASSINIBOINE RIVER AT MILLWOOD (579)	3.0	50.6898	101.4132	67.6
MB05MES035	ASSINIBOINE RIVER AT PR #478, WEST OF BINS-CARTH	4.0	50.6236	101.4178	84.1
MB05MES040	ASSINIBOINE RIVER AT OLD PTH #41, N OF QU'APPELLE RIVER	5.0	50.4408	101.3189	121.8
MB05MES049	ASSINIBOINE RIVER DOWNSTREAM OF THE QU'APPELLE RIVER	6.0	50.4420	101.3192	122.6
MB05MES050	ASSINIBOINE RIVER UPSTREAM OF BIRDTAIL	7.0	50.2809	101.1910	169.0
MB05MES051	ASSINIBOINE RIVER DOWNSTREAM OF BIRDTAIL	8.0	50.2487	101.1743	172.6
MB05MES042	ASSINIBOINE RIVER AT PTH #83, SOUTH OF MINIOTA	9.0	50.1097	101.0356	218.1
MB05MGS040	ASSINIBOINE DOWSTREAM OF ARROW RIVER	10.0	50.0818	100.9318	228.1
MB05MGS034	ASSINIBOINE RIVER AT PR #259, NORTH EAST OF VIRDEN	11.0	49.8744	100.8486	291.5
MB05MGS035	ASSINIBOINE RIVER AT EAST OF VIRDEN	12.0	49.8417	100.8167	304.3
MB05MGS037	ASSINIBOINE RIVER AT PTH #21, NORTH OF GRISWOLD	13.0	49.8425	100.4608	373.3
MB05MGS042	ASSINIBOINE UPSTREAM OF THE LITTLE SASKATCHEWAN RIVER	14.0	49.8722	100.1675	429.9
MB05MHS002	ASSINIBOINE RIVER AT TCH, WEST OF BRANDON	15.0	49.8681	100.0983	435.0
MB05MHS021	ASSINIBOINE RIVER AT 18 TH STREET BRIDGE BRANDON	16.0	49.8606	99.9614	455.0
MB05MES034	BIRDTAIL RIVER, BELOW DAM AT BIRTLE	7.5	50.4208	101.0617	
MB05MES036	QU'APPELLE RIVER AT OLD PTH #41, WEST OF ST. LAZARE	5.5	50.4422	101.3247	
MB05MFS098	LITTLE SASKATCHEWAN RIVER AT PTH #25 NEAR RIVERS	14.5	50.0236	100.2067	

Table 2. Mean discharge (m^3/s) from Lake of the Prairies, two stations on the Assiniboine River, and the three major tributaries to the upper Assiniboine. Median values are based on weekly data for the time periods 1970 to 1999 (Surface Water Management Section 2003).

Month	Outflow from Lake of the Prairies		Assiniboine at Russell			Qu'Appelle River			Birdtail Creek		Little Saskatchewan River		Assiniboine at Brandon		
	2001	2002	2001	2002	Median	2001	2002	Median	2001	2002	2001	2002	2001	2002	Median
January	28.3	2.83	26.29	2.43	9.62	5.4	2.04	4.19			2.5	1.21	36.8	7.93	16.28
February	27.8	2.83	23.99	2.7	8.83	3.63	1.55	3.45			2.51	1.21	32.03	7.81	13.51
March	7.95	1.56	9.64	2.17	9.25	3.42	0.74	3.84	0.73	0.26	1.96	1.36	19.29	7.61	18.61
April	2.8	1.42	22.51	2.44	8.2	43.77	2.42	11.09	17.5	3.91	23.88	6.43	169.77	22.48	61.18
May	2.8	1.42	8.72	1.53	12.05	45.89	1.31	6.2	16.98	1.22	46.58	6.95	233.9	17.15	52.08
June	2.8	1.42	3.9	1.67	11.25	5.11	1.45	4.15	2.77	1.29	13.59	4.77	40.75	12.05	31.86
July	2.8	1.42	3.76	1.45	8.5	6.4	1.22	4.13	3.79	0.4	18.52	4.42	54.96	9.21	25.34
August	2.8	4.02	3.54	4.27	5.44	3.26	3.68	3.18	0.55	0.03	8.18	0.83	22	8.32	14.93
September	4.13	3.11	4.45	3.1	4.69	0.82	3.13	2.78	0.15	0.06	2.6	1.26	8.97	9.9	9.59
October	5.7	4.96	6.26	5.17	6.26	2.6	1.13	6.47	0.46	0.12	1.02	0.73	11.57	7.73	13.59
November	5.22	4.11	5.58	3.98	9.72	5.06	6.44	7.14			1.81	1.04	16.37	9.41	17.63
December	2.8	2.83	3.04	3.11	10.01	3.29	6.5	5.47			1.45	0.68	11.26	11.6	16.93

Table 3: Discharge (m^3/s) at the outlet of Lake of the Prairies, the Assiniboine River, and the three main tributaries, and the resulting incremental inflows and travel times between Lake of the Prairies and the City of Brandon for each sampling period (2001 to 2003).

Sampling Period begins	Release from the outlet of Lake of the Prairies	Assiniboine at Russell	Qu'Appelle River	Birdtail Creek	Assiniboine at Minitota	Little Saskatchewan River	Assiniboine at Brandon	Incremental Inflow	Travel Time from Shellmouth to Brandon (days)
31-May-01	2.8	4.0	3.8	2.0	16.0	10.7	33.4	14.1	12.3
13-Jun-01	2.8	3.8	2.1	2.1	14.5	8.7	29.0	12.2	12.7
26-Jun-01	2.8	3.8	3.1	12.5	64.0	28.8	100.0	19.8	9.7
11-Jul-01	2.8	3.8	4.2	1.4	16.6	12.1	32.3	11.8	12.3
25-Jul-01	2.8	3.7	3.5	1.5	13.4	12.6	29.2	8.8	12.9
8-Aug-01	2.8	3.5	3.8	0.6	11.1	5.9	17.9	4.8	13.6
22-Aug-01	2.8	3.4	2.0	0.1	7.5	3.6	10.8	2.2	14.9
4-Sep-01	2.8	3.5	0.9	0.1	6.8	2.0	8.1	2.1	15.3
19-Sep-01	2.8	3.5	0.7	0.2	6.3	1.1	11.9	7.1	14.8
10-Oct-01	5.7	6.1	3.6	0.5	12.4	1.0	14.3	3.6	12.5
24-Oct-01	5.7	6.2	4.9	0.4	13.2	1.0	15.6	2.4	12.6
19-Nov-01	5.7	6.0	5.5	0.4		1.7	15.7		
17-Dec-01	2.8	3.1	2.6	0.4		1.2	8.1	1.0	15.5
28-Jan-02	2.8	2.7	1.5	0.4		1.2	7.7	1.8	15.9
27-Feb-02	2.8	2.5	1.1	0.4		1.2	8.0	2.4	16.0
3-Apr-02	1.4	1.5	0.6	0.4	6.1	6.1	27.7	19.1	15.0
24-Apr-02	1.4	2.0	2.0	2.6	10.5	7.5	18.8	5.3	14.5
9-May-02	1.4	1.5	1.3	1.0	5.7	5.5	14.6	5.4	16.4
22-May-02	1.4	1.6	1.2	1.1	5.6	3.8	11.6	4.2	16.6
5-Jun-02	1.4	1.7	1.1	1.1	6.9	5.7	11.6	2.3	16.2
19-Jun-02	1.4	1.7	1.4	2.1	9.0	5.9	11.5	0.7	15.6
10-Jul-02	1.4	1.4	1.3	0.3	3.1	1.5	4.4	-0.1	19.5
24-Jul-02	1.4	1.4	1.4	0.05	3.6	0.5	7.2	3.9	17.8
7-Aug-02	4.2	4.5	2.9	0.01	9.0	0.5	9.8	2.2	13.9
21-Aug-02	4.2	4.3	4.8	0.1	13.5	1.1	14.5	4.3	12.8
4-Sep-02	2.8	2.9	3.8	0.1	8.4	1.4	7.9	0	14.9
18-Sep-02	2.8	3.0	2.5	0.04	6.8	1.2	7.4	0.8	15.4
2-Oct-02	5.0	5.3	1.3	0.1	8.2	0.7	7.8	0.8	14.2
15-Oct-02	5.0	5.1	1.1	0.2	6.6	0.7	8.1	1.3	14.2
19-Nov-02	2.8	3.7	12.5	0.02		1.0	12.7	0	13.5
17-Dec-02	2.8	3.3	5.9	0.2		0.5	10.8	1.4	14.1
29-Jan-03	14.1	14.3	2.8	0.02		0.5	16.0	14.1	11.2
5-Mar-03	22.7	23.5	1.5	0.01	23.8	0.5	23.7	-1.0	10.1
21-May-03	22.7	28.3	25.4	1.0	60.8	6.2	61.9	6.6	8.3
11-Jun-03	7.6	8.0	18.2	1.2	32.3	7.8	35.1	0.3	10.4
16-Jul-03	4.3	4.6	11.0	0.1	16.8	3.0	17.5	12.2	12.4
29-Jul-03	8.5	8.4	7.3	0.01	16.5	0.5	17.7	19.8	11.7
Median of all Sample Periods	2.8	3.7	2.6	0.4	9.8	1.5	14.3	2.3	14.1

Table 4. Monthly air temperature and precipitation at Binscarth, Manitoba during 2001 to 2003 (Environment Canada 2003b).

Month	Mean Temperature (°C)	1971-2000 Climate Normals Mean Temperature	Extreme Maximum Temperature (°C)	Extreme Minimum Temperature (°C)	Total Precipitation (mm)	1971-2000 Climate Normals Mean Precipitation
Jan-01	-11.1	-17.7	2.0	-29.0	1.0	24.7
Feb-01	-18.4	-13.4	-0.5	-36.5	12.8	19.1
Mar-01	-7.1	-6.8	4.5	-27.0	22.0	27.5
Apr-01	3.0	3.2	29.0	-13.5	13.4	24.8
May-01	11.6	11.0	29.5	-2.5	62.4	52.5
Jun-01	14.4	15.5	30.5	3.0	129.8	79.5
Jul-01	18.3	18.0	31.0	4.0	93.0	73.1
Aug-01	18.5	16.9	34.0	2.5	18.4	70.6
Sep-01	12.6	11.0	28.0	-4.0	24.2	54.9
Oct-01	3.7	4.3	20.0	-12.5	13.4	30.6
Nov-01	-0.2	-6.4	18.0	-12.0	18.6	20.7
Dec-01	-11.5	-14.8	4.0	-25.0	26.2	23.2
Jan-02	-14.2	-17.7	6.0	-36.0	15.4	24.7
Feb-02	-8.6	-13.4	5.5	-30.0	0.0 ^T	19.1
Mar-02	-13.3	-6.8	5.0	-28.0	24.8	27.5
Apr-02	0.4	3.2	19.0	-18.0	31.0	24.8
May-02	7.7	11.0	30.0	-10.5	11.6	52.5
Jun-02	17.1	15.5	34.0	5.5	123.4	79.5
Jul-02	19.6	18.0	33.0	7.0	52.0	73.1
Aug-02	16.6	16.9	30.0	1.5	176.4	70.6
Sep-02	11.9	11.0	29.0	-6.0	33.4	54.9
Oct-02	-1.4	4.3	21.0	-17.0	25.6	30.6
Nov-02	-6.3	-6.4	9.0	-23.5	14.4	20.7
Dec-02	-9.0	-14.8	3.0	-27.0	75.8	23.2
Jan-03	-17.0	-17.7	4.0	-37.0	3.0	24.7
Feb-03	-18.3	-13.4	-2.0	-37.0	16.0	19.1
Mar-03	-9.5	-6.8	10.5	-37.0	12.0	27.5
Apr-03	4.6	3.2	23.5	-17.0	90.2	24.8
May-03	11.8	11.0	29.0	-2.5	35.0	52.5
Jun-03	16.0	15.5	30.0	4.0	76.2	79.5
Jul-03	18.7	18.0	33.0	4.5	38.4	73.1
Total					1202.2	1134.4

^T = Trace precipitation

Table 5. Mean and range of constituent concentrations along the Assiniboine River for each sampling period during the study (2001 to 2003)

Sampling Period	pH (pH units)	Conductivity ($\mu\text{S}/\text{cm}$)	Color (color units)	Turbidity (NTU)	TDS (mg/L)	TSS (mg/L)	Total alkalinity (mg/L)	Bicarbonate alkalinity (mg/L)	Carbonate alkalinity (mg/L)	Hydroxide alkalinity (mg/L)	Cl ⁻ (mg/L)	DO (mg/L)	BOD ₅ (mg/L)	TOC (mg/L)	TIC (mg/L)	TC (mg/L)	TIC + TC (mg/L)	TPC (mg/L)
30-May-01	Mean 8.21	827	37	23	609	53	278	331	4.3	0.5	19.4	9.65	2.6	14.9	66.2	81.1		
	Range 0.52	393	35	46	255	119	119	152	9.0	0	22.8	3.80	14.0	4.0	28.0	25.0		
13-Jun-01	Mean 8.38	956	17	19	652	39	296	349	5.4	0.5	21.6	9.13	1.5	13.1	71.2	84.4		
	Range 0.21	456	10	27	312	51	107	129	8.4	0	25.7	4.20	2.0	4.0	28.0	27.0		
27-Jun-01	Mean 8.41	841	27	61	559	181	253	301	0.5	0.5	19.5	3.79	2.1	13.2	61.8	74.7		
	Range 0.38	378	35	223	273	86.2	98	120	0.0	0	22.5	4.30	4.0	4.0	23.0	21.0		
14-Jul-01	Mean 8.39	794	31	30	550	68	233	300	2.5	0.5	16.1	6.28	2.7	15.9	62.9	78.6	75.3	3.4
	Range 0.37	364	30	39	141	98	275	146	9.1	0	19.4	5.40	17.0	4.0	14.0	15.0	21.0	10.0
25-Jul-01	Mean 8.35	873	25	21	612	43	275	327	4.1	0.5	19.7	5.45	1.4	14.6	65.9	80.6	78.7	2.2
	Range 0.35	386	25	34	304	61	103	117	8.1	0	25.7	4.60	1.0	5.0	26.0	24.0	26.0	4.0
8-Aug-01	Mean 8.33	878	25	23	609	54	302	357	5.8	0.5	21.6	6.18	2.6	14.4	63.2	77.5	75.7	1.9
	Range 0.30	475	15	30	339	72	105	135	12.4	0	35.1	3.70	22.0	5.0	24.0	26.0	26.0	3.0
22-Aug-01	Mean 8.31	846	17	19	627	43	256	300	6.4	0.5	23.1	7.13	2.5	14.5	61.0	75.6	74.4	1.7
	Range 0.51	428	5	16	323	59	88	117	15.6	0	31.1	6.90	4.0	5.0	21.0	19.0	24.0	6.0
4-Sep-01	Mean 8.39	831	15	16	611	34	257	300	6.9	0.5	21.0	7.62	5.6	14.2	61.9	75.9	75.9	1.0
	Range 0.34	320	10	19	252	47	64	89	13.1	0	23.6	4.50	7.0	3.0	18.0	16.0	16.0	0.0
19-Sep-01	Mean 8.28	808	11	15	593	26	267	320	3.2	0.5	17.7	7.15	1.1	12.9	63.5	76.3	76.4	1.1
	Range 0.27	298	5	22	218	44	79	100	8.5	0	19.0	3.60	1.0	3.0	19.0	17.0	16.0	1.0
10-Oct-01	Mean 8.25	747	12	9	546	18	252	301	3.4	0.5	14.0	8.66	1.5	14.3	60.3	74.5	71.1	3.9
	Range 0.17	157	5	16	138	22	50	62	6.9	0	9.1	10.80	2.0	3.0	13.0	12.0	9.0	6.0
21-Oct-01	Mean 8.31	787	9	6	592	16	247	293	4.2	0.5	18.9	7.99	2.2	13.8	60.2	74.2	73.0	2.0
	Range 0.19	224	9	8	178	15	71	79	6.5	0	21.6	9.00	4.0	6.1	19.0	20.0	15.0	5.0
19-Nov-01	Mean 8.32	914	10	7	576	15	247	295	3.1	0.5	24.5	9.91	1.4	12.4	56.7	69.1	68.3	1.2
	Range 0.24	470	10	13	390	27	39	50	5.4	0	39.2	12.60	1.0	5.3	9.0	8.0	7.0	1.0
17-Dec-01	Mean 8.15	961	14	4	663	7	278	338	1.3	0.5	23.0	9.63	1.5	13.4	63.1	76.6	71.4	5.2
	Range 0.43	430	13	5	365	9	84	115	5.2	0	29.2	3.00	1.0	3.0	20.0	21.0	16.0	10.0
28-Jan-02	Mean 8.02	922	9	4	650	6	275	336	0.6	0.5	18.3	6.13	1.3	10.8	69.6	80.4	79.2	1.0
	Range 0.42	332	5	5	188	10	74	93	0.8	0	19.7	7.00	0.7	2.0	21.0	20.0	20.0	0.0
27-Feb-02	Mean 7.99	936	6	4	655	8	287	350	0.5	0.5	20.2	7.40	3.1	10.1	64.1	78.9	78.0	1.3
	Range 0.33	278	4	9	173	21	69	84	0.0	0	18.5	5.80	4.0	3.2	18.0	16.0	17.0	1.0
3-Apr-02	Mean 7.95	949	9	3	719	5	308	375	0.5	0.5	21.3	6.55	1.0	10.7	74.3	85.0	82.5	1.3
	Range 0.32	353	20	4	280	8	82	101	0.0	0	32.3	3.50	0.0	5.9	23.0	18.0	19.0	1.0
24-Apr-02	Mean 8.30	781	27	37	524	90	199	242	0.8	0.5	14.8	7.59	3.5	13.1	48.5	61.5	59.0	2.8
	Range 0.27	553	38	56	318	154	96	118	2.8	0	18.7	7.10	3.0	6.0	23.0	27.0	23.0	4.0
8-May-02	Mean 8.54	893	12	12	617	29	261	302	8.2	0.5	19.0	9.62	4.4	12.3	61.5	73.5	69.3	4.2
	Range 0.53	474	13	29	243	38	96	127	11.4	0	26.1	5.90	5.0	3.0	22.0	22.0	24.0	7.0
22-May-02	Mean 8.34	909	9	17	650	34	283	337	4.0	0.5	21.1	7.87	5.0	21.5	59.1	80.5	80.3	1.1
	Range 0.24	419	8	28	262	49	86	95	6.6	0	30.3	2.90	3.0	31.0	34.0	20.0	20.0	2.0
5-Jun-02	Mean 8.35	944	13	18	599	40	281	340	1.8	0.5	20.8	7.55	3.4	10.5	67.9	78.4	71.3	6.6
	Range 0.29	296	10	33	428	67	79	97	6.6	0	20.0	5.00	5.0	4.3	17.0	16.0	16.0	12.0
19-Jun-02	Mean 8.37	914	13	21	626	44	274	329	2.8	0.5	20.5	7.41	2.6	13.0	65.9	78.4	71.9	6.5
	Range 0.39	405	5	29	310	65	77	94	11.4	0	27.0	3.60	5.0	4.0	21.0	21.0	26.0	11.0
10-Jul-02	Mean 8.29	922	18	17	640	34	251	301	3.0	0.5	19.3	7.40	3.6	12.0	59.5	71.4	62.5	9.2
	Range 0.48	370	25	23	286	50	82	110	6.7	0	20.9	5.50	5.0	2.0	23.0	22.0	24.0	13.0
24-Jul-02	Mean 8.48	895	10	15	603	29	246	284	3.4	0.5	25.4	7.58	3.8	11.1	58.1	69.0	67.2	1.8
	Range 0.56	284	9	18	194	43	98	148	13.8	0	25.2	4.40	3.0	3.3	25.0	22.0	21.0	2.0

Table 5. Mean and range of constituent concentrations along the Assiniboine River for each sampling period during the study (2001 to 2003) (continued...).

Sampling Period	pH (unit)	Conductivity (µS/cm)	Color (color units)	Turbidity (NTU)	TDS (mg/L)	TSS (mg/L)	Total alkalinity (mg/L)	Bicarbonate alkalinity (mg/L)	Carbonate alkalinity (mg/L)	Hydroxide alkalinity (mg/L)	Cl ⁻ (mg/L)	DO (mg/L)	BOD (mg/L)	TOC (mg/L)	THC (mg/L)	TC (mg/L)	THC (mg/L)	TPC (mg/L)
7-Aug-02	Mean 8.33	862	32	19	603	42	230	280	0.8	0.5	19.7	6.87	3.3	12.7	53.8	66.5	64.8	1.7
21-Aug-02	Range 0.28	315	80	25	226	66	86	105	4.3	0	19.6	2.40	5.0	7.0	21.0	18.0	18.0	4.0
	Mean 8.56	866	11	15	580	34	215	258	2.2	0.5	34.2	8.04	11.3	13.4	48.5	61.9	60.0	2.1
4-Sep-02	Range 0.45	244	10	20	185	53	34	57	6.7	0	26.6	2.70	31.0	4.0	12.0	10.0	11.0	5.0
	Mean 8.36	929	17	16	634	41	225	273	1.2	0.5	29.8	7.57	5.2	12.0	51.7	63.7	62.9	1.1
18-Sep-02	Range 0.68	348	7	26	268	70	32	34	4.3	0	33.8	4.70	17.0	5.0	17.0	14.0	15.0	1.0
	Mean 8.24	954	10	21	666	47	239	282	0.8	0.5	27.1	6.90	7.0	11.5	55.7	67.1	66.5	1.1
2-Oct-02	Range 0.38	367	7	29	325	87	40	49	0.0	0	32.6	2.50	7.0	8.0	7.0	7.0	7.0	1.0
	Mean 8.26	888	9	14	636	27	241	293	0.5	0.5	22.3	7.91	6.2	12.1	57.8	69.7	68.7	1.2
15-Oct-02	Range 0.23	331	8	18	272	31	46	56	0.0	0	27.4	5.30	9.0	4.0	11.0	9.0	9.0	1.0
	Mean 8.53	837	9	10	588	20	241	294	0.5	0.5	18.2	8.96	5.3	11.5	58.0	69.7	68.3	1.6
19-Nov-02	Range 0.32	992	8	6	719	17	250	305	0.5	0.5	27.9	9.56	2.6	11.0	55.6	66.5	65.9	1.0
	Mean 7.87	654	4	11	518	26	68	83	0.0	0	58.9	3.00	2.0	2.0	14.0	13.0	14.0	0.0
17-Dec-02	Range 0.46	1049	8	11	690	21	233	282	1.7	0.5	36.5	7.72	4.6	11.2	58.0	69.3	62.9	6.4
	Mean 0.28	561	5	47	369	97	166	203	6.7	0	57.0	3.70	5.0	1.0	14.0	13.0	7.0	6.0
28-Jan-03	Range 0.18	913	9	11	592	20	242	296	0.5	0.5	17.6	9.16	3.6	10.6	61.6	72.1	70.9	1.1
	Mean 7.59	242	2	14	200	28	58	71	0.0	0	16.6	3.60	9.0	1.0	9.0	10.0	8.0	0.5
5-Mar-03	Range 0.13	869	10	15	609	28	248	302	0.5	0.5	14.4	9.31	1.0	10.0	57.1	67.0	65.9	1.4
	Mean 0.41	158	0	23	98	44	15	18	0.0	0	10.2	3.00	0.0	1.4	5.0	4.0	4.0	1.2
21-May-03	Range 0.08	848	20	50	588	150	214	261	0.6	0.5	34.5	8.97	2.3	10.9	51.3	62.1	57.8	4.4
	Mean 8.79	368	5	81	288	232	48	59	1.9	0	29.2	3.40	1.0	3.7	10.0	10.0	10.0	9.0
11-Jun-03	Range 0.66	944	14	52	650	136	221	269	0.5	0.5	32.4	7.37	1.9	12.4	51.4	63.9	60.7	3.9
	Mean 0.56	716	10	80	511	224	54	66	0.0	0	58.3	3.00	2.0	4.0	11.0	9.0	28.0	21.0

Table 5. Mean and range of constituent concentrations along the Assiniboine River for each sampling period during the study (2001 to 2003) (continued...).

Sampling Period	NO ₃ -N (mg/L)	NH ₄ ⁺ (mg/L)	STN (mg/L)	TKN (mg/L)	PTKN (mg/L)	TN (mg/L)	TON (mg/L)	Ortho-P (mg/L)	TP (mg/L)	PP (mg/L)	TDP (mg/L)	TOP (mg/L)	C-Na (µg/L)	D-Fe (mg/L)	D-Mg (mg/L)
30-May-01	Mean	0.051	1.056	1.056	1.056	1.108	0.998	0.072	0.158	0.094	0.061	0.086	16.4	0.099	0.002
	Range	0.290	1.100	1.100	1.100	1.150	1.080	0.072	0.290	0.275	0.069	0.255	26.0	0.020	0.014
13-Jun-01	Mean	0.037	1.413	1.413	1.413	1.451	1.374	0.057	0.124	0.074	0.057	0.068	20.5	0.011	0.004
	Range	0.180	1.200	1.200	1.200	1.200	1.210	0.078	0.123	0.077	0.058	0.058	20.2	0.020	0.018
27-Jun-01	Mean	0.156	1.523	1.523	1.523	1.679	1.441	0.272	0.319	0.237	0.082	0.047	15.2	0.090	0.001
	Range	0.360	2.200	2.200	2.200	2.340	2.070	1.029	1.139	1.005	0.136	0.145	18.9	0.100	0.001
11-Jul-01	Mean	0.076	0.718	0.718	0.718	0.718	0.718	0.156	0.212	0.128	0.086	0.056	16.7	0.284	0.040
	Range	0.270	1.050	1.050	1.050	1.050	1.050	0.199	0.199	0.193	0.104	0.083	16.3	0.890	0.209
25-Jul-01	Mean	0.126	0.921	0.921	0.921	1.048	0.846	0.122	0.162	0.069	0.093	0.040	11.4	0.060	0.002
	Range	0.310	1.000	1.000	1.000	1.090	0.970	0.131	0.151	0.127	0.107	0.091	15.6	0.190	0.003
8-Aug-01	Mean	0.045	0.687	0.687	0.687	0.687	0.687	0.128	0.177	0.095	0.082	0.049	21.8	0.010	0.003
	Range	0.100	0.900	0.900	0.900	0.930	0.930	0.191	0.142	0.102	0.127	0.158	54.4	0.009	0.000
22-Aug-01	Mean	0.053	0.707	0.707	0.707	0.707	0.707	0.063	0.155	0.103	0.052	0.092	34.2	0.010	0.003
	Range	0.340	0.400	0.400	0.400	0.620	0.620	0.102	0.077	0.114	0.069	0.082	58.9	0.009	0.001
4-Sep-01	Mean	0.032	0.873	0.873	0.873	1.053	0.958	0.088	0.136	0.090	0.047	0.049	5.5	0.010	0.003
	Range	0.090	1.100	1.100	1.100	1.100	1.020	0.102	0.062	0.111	0.123	0.072	8.6	0.020	0.020
19-Sep-01	Mean	0.028	0.707	0.707	0.707	0.707	0.707	0.093	0.120	0.059	0.060	0.026	7.2	0.084	0.001
	Range	0.030	0.800	0.800	0.800	0.800	0.800	0.093	0.120	0.059	0.060	0.026	7.2	0.084	0.001
10-Oct-01	Mean	0.090	0.687	0.687	0.687	0.687	0.687	0.082	0.079	0.046	0.095	0.022	14.6	0.000	0.000
	Range	0.290	0.300	0.300	0.300	0.300	0.300	0.082	0.079	0.046	0.095	0.022	14.6	0.000	0.000
24-Oct-01	Mean	0.044	0.282	0.282	0.282	0.282	0.282	0.079	0.121	0.050	0.072	0.020	14.3	0.010	0.003
	Range	0.180	0.300	0.300	0.300	0.300	0.300	0.079	0.121	0.050	0.072	0.020	14.3	0.010	0.003
19-Nov-01	Mean	0.092	0.553	0.553	0.553	0.553	0.553	0.076	0.101	0.047	0.054	0.025	12.5	0.010	0.003
	Range	0.220	0.800	0.800	0.800	0.800	0.800	0.076	0.101	0.047	0.054	0.025	12.5	0.010	0.003
17-Dec-01	Mean	0.102	0.776	0.776	0.776	0.776	0.776	0.057	0.080	0.029	0.052	0.043	12.3	0.010	0.003
	Range	0.128	0.600	0.600	0.600	0.600	0.600	0.057	0.080	0.029	0.052	0.043	12.3	0.010	0.003
28-Jan-02	Mean	0.227	0.533	0.533	0.533	0.533	0.533	0.061	0.074	0.024	0.031	0.018	32.8	0.000	0.001
	Range	0.400	0.900	0.900	0.900	0.900	0.900	0.061	0.074	0.024	0.031	0.018	32.8	0.000	0.001
27-Feb-02	Mean	0.352	0.433	0.433	0.433	0.433	0.433	0.034	0.030	0.010	0.014	0.005	2.4	0.020	0.045
	Range	0.400	0.900	0.900	0.900	0.900	0.900	0.034	0.030	0.010	0.014	0.005	2.4	0.020	0.045
3-Apr-02	Mean	0.424	0.108	0.108	0.108	0.108	0.108	0.032	0.036	0.040	0.021	0.018	145.5	0.010	0.059
	Range	0.340	0.270	0.270	0.270	0.270	0.270	0.032	0.036	0.040	0.021	0.018	145.5	0.010	0.059
24-Apr-02	Mean	0.330	0.070	0.070	0.070	0.070	0.070	0.048	0.073	0.034	0.039	0.025	4.2	0.012	0.093
	Range	0.873	0.607	0.607	0.607	0.607	0.607	0.048	0.073	0.034	0.039	0.025	4.2	0.012	0.093
8-May-02	Mean	0.030	0.040	0.040	0.040	0.040	0.040	0.043	0.060	0.049	0.033	0.031	2.9	0.010	0.115
	Range	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.060	0.049	0.033	0.031	2.9	0.010	0.115
22-May-02	Mean	0.010	0.047	0.047	0.047	0.047	0.047	0.033	0.239	0.180	0.059	0.008	14.8	0.022	0.003
	Range	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.239	0.180	0.059	0.008	14.8	0.022	0.003
5-Jun-02	Mean	0.010	0.860	0.860	0.860	0.860	0.860	0.062	0.136	0.109	0.031	0.019	8.2	0.010	0.003
	Range	0.000	0.000	0.000	0.000	0.000	0.000	0.062	0.136	0.109	0.031	0.019	8.2	0.010	0.003
19-Jun-02	Mean	0.030	0.247	0.247	0.247	0.247	0.247	0.096	0.132	0.094	0.018	0.036	15.5	0.000	0.000
	Range	0.280	0.400	0.400	0.400	0.400	0.400	0.096	0.132	0.094	0.018	0.036	15.5	0.000	0.000
10-Jul-02	Mean	0.010	0.200	0.200	0.200	0.200	0.200	0.171	0.109	0.076	0.078	0.045	8.8	0.010	0.003
	Range	0.000	0.000	0.000	0.000	0.000	0.000	0.171	0.109	0.076	0.078	0.045	8.8	0.010	0.003
24-Jul-02	Mean	0.010	0.200	0.200	0.200	0.200	0.200	0.212	0.147	0.085	0.066	0.049	5.6	0.010	0.003
	Range	0.000	0.000	0.000	0.000	0.000	0.000	0.212	0.147	0.085	0.066	0.049	5.6	0.010	0.003
7-Aug-02	Mean	0.011	0.600	0.600	0.600	0.600	0.600	0.102	0.154	0.085	0.070	0.053	23.7	0.010	0.003
	Range	0.010	0.100	0.100	0.100	0.100	0.100	0.102	0.154	0.085	0.070	0.053	23.7	0.010	0.003

Table 5. Mean and range of constituent concentrations along the Assiniboine River for each sampling period during the study (2001 to 2003) (continued...).

Sampling Period	NO ₃ -NO ₂ (mg/L)	NH ₃ (mg/L)	STKN (mg/L)	TKN (mg/L)	PTKN (mg/L)	TN (mg/L)	TON (mg/L)	OrthoP (mg/L)	TP (mg/L)	PP (mg/L)	TDP (mg/L)	TOP (mg/L)	Chla (µg/L)	D Fe (mg/L)	D Mg (mg/L)
21-Aug-02	Mean	0.364	0.056	0.207	0.347	0.340	0.711	0.291	0.066	0.127	0.071	0.057	65.9	0.010	0.005
	Range	1.490	0.300	0.100	0.900	0.900	1.790	1.040	0.121	0.156	0.165	0.140	182.9	0.000	0.026
4-Sep-02	Mean	0.053	0.113	0.600	1.033	0.507	1.086	0.920	0.101	0.177	0.117	0.060	76.2	0.010	0.017
	Range	0.340	0.370	0.400	1.700	1.200	1.710	1.720	0.168	0.208	0.196	0.212	223.3	0.000	0.079
18-Sep-02	Mean	0.044	0.091	0.320	0.933	0.727	0.977	0.842	0.056	0.171	0.104	0.067	115	0.010	0.003
	Range	0.210	0.170	0.500	2.700	2.700	2.700	2.690	0.182	0.192	0.117	0.153	29.6	0.000	0.006
2-Oct-02	Mean	0.010	0.078	0.373	0.187	0.200	0.397	0.309	0.058	0.132	0.081	0.070	14.8	0.010	0.003
	Range	0.090	0.110	0.800	0.900	0.600	0.900	0.850	0.170	0.083	0.068	0.140	18.4	0.000	0.006
15-Oct-02	Mean	0.010	0.047	0.727	1.200	0.467	1.210	1.153	0.079	0.146	0.077	0.069	27.7	0.037	0.023
	Range	0.090	0.150	0.400	0.800	0.500	0.800	0.770	0.100	0.085	0.071	0.120	45.5	0.150	0.081
19-Nov-02	Mean	0.153	0.131	0.325	0.125	0.200	0.478	0.194	0.077	0.117	0.053	0.064	31.1	0.155	0.093
	Range	0.060	0.250	0.500	0.500	0.600	0.550	0.500	0.107	0.066	0.055	0.087	88.6	0.280	0.114
17-Dec-02	Mean	0.157	0.116	0.978	1.389	0.678	1.546	1.273	0.062	0.130	0.069	0.061	48.3	0.110	0.007
	Range	0.150	0.040	1.000	1.100	1.000	1.240	1.080	0.079	0.260	0.257	0.024	197.7	0.000	0.012
28-Jan-03	Mean	0.329	0.128	0.533	0.600	0.244	0.929	0.472	0.087	0.116	0.049	0.067	5.9	0.010	0.004
	Range	0.170	0.070	0.900	1.000	0.300	1.160	1.060	0.061	0.051	0.046	0.009	4.9	0.000	0.006
5-Mar-03	Mean	0.322	0.054	1.056	1.122	0.200	1.444	1.068	0.056	0.119	0.067	0.052	5.3	0.030	0.005
	Range	0.200	0.060	0.100	0.300	0.000	0.430	0.350	0.020	0.082	0.007	0.007	5.2	0.000	0.008
21-May-03	Mean	0.197	0.085	0.307	0.727	0.547	0.923	0.641	0.054	0.252	0.198	0.054	23.7	0.025	0.017
	Range	0.200	0.080	0.300	1.100	1.100	1.350	1.110	0.077	0.288	0.266	0.028	31.2	0.230	0.167
11-Jun-03	Mean	0.014	0.071	0.829	1.836	1.036	1.850	1.764	0.039	0.275	0.233	0.042	30.1	0.033	0.005
	Range	0.060	0.110	0.700	4.600	4.400	4.600	4.600	0.087	0.438	0.393	0.070	31.2	0.030	0.019

Table 6. Model accuracy and precision for the June 5 2002 water quality model (* not normally distributed).

Variable	Final Model		Percent Mean Difference		Initial Model		Percent Mean Difference
	r ²	P			r ²	P	
Conductivity	0.76	<0.0001	8.73		0.76	<0.0001	8.73
DO	0.50	0.0047	0.62		0.73	<0.0001	2.69
TON	0.27	0.0576	2.44		0.26	0.0502	1.89
NH ₃		below detection				below detection	
NO ₂ NO ₃		below detection				below detection	
TN	0.28	0.0542	1.69		0.27	0.0469	1.16
TOP			0.74				1.30
InorgP	0.74	<0.0001	3.09		0.72	<0.0001	0.06
TP	0.69	0.0002	3.39		0.65	0.0003	1.67
Chl <i>a</i>	0.56	0.0020	0.63		0.50	0.0030	1.88
TSS	0.38*	0.0189	26.61		0.37*	0.0158	25.77

Table 7. Model accuracy and precision for the June 19 2002 water quality model (* not normally distributed).

Variable	Final Model		Percent Mean Difference		Initial Model		After Manipulation	
	r ²	P			r ²	P	r ²	P
Conductivity	0.50	0.0045	9.89		0.50	0.0045	0.50	0.0045
DO			7.56				0.58	0.0016
TON			4.56					4.57
NH ₃		below detection						below detection
NO ₂ NO ₃		below detection						below detection
TN			1.79					1.80
TOP			170.30					180.61
InorgP	0.37*	0.0201	0.83		0.37*	0.0201	0.38*	0.0194
TP	0.28	0.0519	32.66		0.28	0.0519	0.30	0.0443
Chl <i>a</i>			60.08					64.91
TSS	0.30*	0.0446	24.92		0.30*	0.0446	0.30*	0.0446

Table 8. Model accuracy and precision for the July 24 2002 water quality model.

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.82	<0.0001	2.01	0.82	<0.0001	2.01	0.82	<0.0001	2.01
DO	0.42	0.0118	0.43			4.54	0.77	<0.0001	0.86
TON		below detection			below detection			below detection	
NH ₃	0.38	0.0193	73.74	0.38	0.0192	73.74	0.35	0.0262	38.88
NO ₂ NO ₃		below detection			below detection			below detection	
TN			14.38			14.39			14.23
TOP	0.29	0.0464	13.39	0.29	0.0464	13.39	0.26	0.0598	3.77
InorgP	0.56	0.0020	27.03	0.56	0.0020	27.00	0.67	0.0004	9.17
TP	0.59	0.0014	18.80	0.59	0.0014	18.78	0.68	0.0003	4.36
Chl <i>a</i>			76.16			76.21	0.31	0.0397	33.41
TSS	0.59	0.0014	30.01	0.59	0.0014	30.01	0.57	0.0014	30.83

Table 9. Model accuracy and precision for the June 13 2001 water quality model (* not normally distributed).

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.96	<0.0001	14.26	0.96	<0.0001	14.26	0.96	<0.0001	14.26
DO	0.50	0.0100	19.25			15.33			3.23
TON			5.34			5.46			5.59
NH ₃			37.50			37.94			18.69
NO ₂ NO ₃	0.98*	<0.0001	69.87	0.98*	<0.0001	70.28	0.98*	<0.0001	44.94
TN			7.89			8.02			7.16
TOP	0.54	0.0028	9.54	0.53	0.0031	9.18	0.53	0.0032	0.20
InorgP	0.84	<0.0001	46.87	0.84	<0.0001	46.38	0.97	<0.0001	0.01
TP	0.90	<0.0001	16.11	0.90	<0.0001	16.1	0.93	<0.0001	0.84
Chl <i>a</i>			45.87			44.84			17.74
TSS	0.58	0.0016	33.41	0.58	0.0017	33.46	0.58	0.0016	34.71

Table 10. Model accuracy and precision for the May 9 2002 water quality model (* not normally distributed).

Variable	Final Model		
	r^2	P	Percent Mean Difference
Conductivity	0.89	<0.0001	0.78
DO	0.33	0.0394	2.23
TON			2.04
NH ₃		below detection	
NO ₂ NO ₃		below detection	
TN			3.10
TOP			9.36
InorgP	0.44	0.0131	43.77
TP	0.31*	0.0474	26.61
Chl <i>a</i>			37.85
TSS	0.34*	0.0360	25.02

Table 11. Model accuracy and precision for the July 25 2001 water quality model (* not normally distributed).

Variable	Final Model			Initial Model		
	r^2	P	Percent Mean Difference	r^2	P	Percent Mean Difference
Conductivity	0.91	<0.0001	9.65	0.91	<0.0001	9.65
DO			29.10	0.91	<0.0001	0.20
TON	0.54	0.0066	22.17	0.54	0.0064	23.50
NH ₃			120.16			11.12
NO ₂ NO ₃			39.03			39.13
TN	0.68	0.0009	14.80	0.67	0.0012	10.28
TOP			225.73			206.07
InorgP	0.62*	0.0023	36.23	0.82	<0.0001	1.80
TP	0.56	0.0052	20.92	0.61*	0.0026	4.17
Chl <i>a</i>	0.57	0.0044	85.09	0.66	0.0014	107.61
TSS			36.64			36.36

Table 12. Model accuracy and precision for the August 8 2001 water quality model (* not normally distributed).

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.93	<0.0001	7.55	0.93	<0.0001	7.55	0.93	<0.0001	7.55
DO	0.74	0.0007	9.77			8.17	0.71*	0.0011	0.37
TON			23.18			23.57			31.35
NH ₃			157.40			48.87			10.90
NO ₂ NO ₃			11.88			1.18			56.41
TN			21.20			18.44			21.20
TOP			240.21			230.45			222.49
InorgP	0.80	<0.0001	41.13	0.73	0.0002	6.29	0.81	<0.0001	10.32
TP	0.86	<0.0001	16.02	0.86*	<0.0001	11.72	0.86	<0.0001	12.46
Chl <i>a</i>			28.45			44.69			0.49
TSS	0.72	0.0003	43.52	0.72	0.0003	43.45	0.68	0.0006	38.99

Table 13. Model accuracy and precision for July 24 2002 water quality model.

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.82	<0.0001	2.14	0.82	<0.0001	2.14	0.82	<0.0001	2.14
DO			6.45			17.00	0.76	<0.0001	2.12
TON			TKN below detection			TKN below detection		TKN below detection	
NH ₃	0.34	0.0299	11.22	0.35	0.0268	63.90	0.33	0.0303	11.13
NO ₂ NO ₃			Below detection			Below detection		Below detection	
TN			TKN below detection			TKN below detection		TKN below detection	
TOP			6.63			36.28			6.73
InorgP	0.68	0.0030	17.43	0.41	0.0142	148.05	0.68	0.0003	17.33
TP	0.68	0.0003	10.51	0.36	0.0238	82.37	0.68	0.0003	10.48
-Chl <i>a</i>			76.32			19.81			76.84
TSS	0.64	0.0006	45.36	0.64	0.0006	46.81	0.64	0.0006	45.35

Table 14. Model accuracy and precision for the August 7 2002 water quality model (* not normally distributed, ^x outlier removed).

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.87	<0.0001	3.63	0.87	<0.0001	3.63	0.87	<0.0001	3.63
DO	0.39	0.0165	0.87			15.07	0.61	0.0009	1.92
TON	0.56	0.0022	1.83	0.57	0.0018	2.98	0.37	0.0216	42.32
NH ₃	0.44	0.0092	211.24	0.56*	0.0020	35.99	0.65*	0.0005	4.84
NO ₂ NO ₃		Below detection			Below detection			Below detection	
TN	0.59	0.0014	14.91	0.59	0.0013	0.95	0.39	0.0168	21.68
TOP			59.84			3.44			69.69
InorgP	0.86	<0.0001	7.87	0.81	<0.0001	67.35	0.85	<0.0001	9.83
TP	0.51	0.0043	3.65	0.48	0.0060	33.6	0.46	0.0077	10.20
Chl <i>a</i>	0.50	0.0045	36.44	0.59 ^x	0.0021	62.32			36.01
TSS	0.52	0.0036	61.81	0.53	0.0031	62	0.42	0.0126	53.65

Table 15. Model accuracy and precision for August 21 2002 water quality model.

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.89	<0.0001	0.95	0.89	<0.0001	0.95	0.89	<0.0001	0.95
DO			16.99			33.59	0.65	0.0003	0.09
TON			239.83			246.18			253.68
NH ₃			758.08			367.33			110.65
NO ₂ NO ₃			332.68	0.65	0.0003	329.88	0.80	<0.0001	505.84
TN			195.16			176.08			179.56
TOP			170.61			167.16			229.35
InorgP			168.89			252.09			113.69
TP			152.03			192.09	0.40	0.0114	142.83
Chl <i>a</i>	0.57	0.0012	12.37	0.60	0.0008	0.79	0.59	0.0008	0.18
TSS	0.70	<0.0001	23.12	0.69	0.0001	22.64	0.61	0.0005	13.36

Table 16. Model accuracy and precision for the September 19 2001 water quality model (* not normally distributed).

Variable	Final Model			Initial Model		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.99	<0.0001	8.89	0.99	<0.0001	8.89
DO	0.55	0.0058	4.90	0.86	<0.0001	0.73
TON			8.81			7.55
NH ₃	0.84	<0.0001	31.71	0.69	0.0002	1.23
NO ₂ NO ₃	0.45*	0.0084	37.73	0.44	0.0098	27.32
TN	0.55	0.0023	11.90	0.57	0.0019	5.33
TOP	0.57	0.0017	4.87	0.55	0.0024	9.40
InorgP	0.71	0.0001	7.82	0.71	0.0002	6.27
TP	0.56	0.0020	6.71	0.56	0.0020	6.75
Chl <i>a</i>	0.64*	0.0006	12.94	0.66*	0.0004	5.01
TSS	0.49	0.0056	48.35	0.49	0.0056	48.08

Table 17. Model accuracy and precision for the September 4 2001 water quality model.

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.90	<0.0001	10.78	0.90	<0.0001	10.78	0.90	<0.0001	10.78
DO			10.23			6.68	0.99	<0.0001	0.03
TON	0.45	0.0117	6.72	0.44	0.0032	7.35	0.45	0.0028	6.76
NH ₃	0.69	0.0005	0.02	0.56	0.0033	45.91	0.69	0.0005	0.17
NO ₂ NO ₃	0.32	0.0456	40.30			174.48			41.93
TN	0.57	0.0029	5.69	0.56	0.0034	12.26	0.57	0.0029	5.77
TOP			16.41			13.27			16.23
InorgP	0.71	0.0003	2.30	0.72	0.0003	1.56	0.71	0.0003	2.20
TP	0.43	0.0156	12.98	0.43	0.0155	12.93	0.43	0.0156	13.01
Chl <i>a</i>	0.70	0.0003	41.43	0.52	0.0054	33.22	0.70	0.0003	42.17
TSS			46.93			46.74			46.92

Table 18. Model accuracy and precision for the October 10 2001 water quality model (* not normally distributed).

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.88	<0.0001	0.23	0.88	<0.0001	0.23	0.88	<0.0001	0.23
DO			16.64			7.12	0.71*	<0.0001	2.52
TON			4.01			14.88			19.47
NH ₃			12.79			5.54			22.15
NO ₂ NO ₃	0.63	0.0006	245.14	0.55	0.0023	299.24	0.61	0.0010	187.18
TN	0.64	0.0006	12.82	0.53	0.0031	26.01	0.50	0.0047	23.44
TOP	0.54	0.0028	22.59	0.32	0.0364	26.56	0.50	0.0049	23.02
InorgP	0.49	0.0056	21.31	0.38	0.0194	44.86	0.86	<0.0001	23.11
TP	0.51	0.0041	5.58			35.34	0.75	<0.0001	22.46
Chl <i>a</i>			32.78	0.49	0.0055	19.38	0.64	0.0006	22.09
TSS			25.06			20.53			18.81

Table 19. Model accuracy and precision for the September 18 2002 water quality model (* not normally distributed).

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.96	<0.0001	6.79	0.96	<0.0001	6.79	0.96	<0.0001	6.79
DO	0.32	0.0350	4.81			9.69	0.83	<0.0001	0.58
TON			140.67			111.23			142.63
NH ₃			37.04			61.44			159.15
NO ₂ NO ₃			59.1			31.13			268.05
TN			50.37			33.31			81.16
TOP	0.75	0.0001	36.13			15.32	0.88	<0.0001	19.84
InorgP	0.39	0.0161	314.29	0.65	0.0005	397.52	0.79	<0.0001	173.24
TP	0.49	0.0081	7.21	0.40	0.0154	15.01			2.23
Chl <i>a</i>			46.32			0.81	0.73*	0.0002	9.35
TSS	0.38	0.0181	42.15	0.33*	0.0313	40.34	0.34*	0.0359	39.43

Table 20. Model accuracy and precision for the October 15 2002 water quality model.

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.87	<0.0001	5.96	0.87	<0.0001	5.96	0.87	<0.0001	5.96
DO			6.73			0.17	0.94	<0.0001	1.46
TON			5.56			5.99			5.98
NH ₃	0.64	0.0006	69.93	0.70	0.0002	69.62	0.65	0.0005	33.56
NO ₂ NO ₃			6.72			10.77			28.82
TN	0.40	0.0156	7.19	0.35	0.0261	7.3	0.44	0.0094	6.62
TP	0.65	0.0005	8.63	0.67	0.0004	16.82	0.62	0.0008	10.38
InorgP			76.62			86.16	0.70	0.0002	51.24
TP			30.90			36.35			22.11
Chl <i>a</i>	0.37	0.0200	4.62			0.76	0.45	0.0083	22.15
TSS	0.66	0.0004	36.19	0.63	0.0007	34.02	0.68	0.0003	35.82

Table 21. Model accuracy and precision for the January 2002 water quality model.

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.95	<0.0001	8.09	0.95	<0.0001	8.09			
DO	0.84	0.0014	13.19	0.75	0.0052	7.84			
TON			83.59			83.62			
NH ₃			33.05			15.96			
NO ₂ NO ₃	0.95	<0.0001	25.63	0.95	<0.0001	22.52			
TN	0.86	0.0009	5.62	0.81	0.0023	10.24			
TP			14.35			2.08			
InorgP	0.78	0.0034	8.81	0.95	<0.0001	3.23			
TP	0.66	0.0148	9.93	0.95	<0.0001	2.64			
Chl <i>a</i>	0.70	0.0099	10.74	0.70	0.0098	10.37			
TSS			43.70			43.68			

Table 22. Model accuracy and precision for the February 2002 water quality model (^x outlier removed).

Variable	Final Model			Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.95	<0.0001	7.45	0.95	<0.0001	7.45	0.95	<0.0001	7.45
DO	0.96	<0.0001	1.96	0.79	0.0014	4.29	0.94	<0.0001	4.78
TON			169.10			169.29			166.48
NH ₃	0.80	0.0011	40.00	0.66	0.0074	77.5	0.80	0.0010	40.56
NO ₂ NO ₃	0.90	<0.0001	16.70	0.92	<0.0001	18.59	0.91	<0.0001	16.89
TN			56.54			62.71			55.92
TOP			55.34			73.87			40.35
InorgP	0.96 ^x	<0.0001	5.50	0.57	0.0155	5.35	0.97 ^x	<0.0001	4.05
TP	0.96 ^x	<0.0001	0.98			8.55	0.96 ^x	<0.0001	1.25
Chl <i>a</i>	0.74	0.0027	48.69	0.74	0.0024	50.32	0.75	0.0024	22.93
TSS	0.80 ^x	0.0028	28.36			36.07	0.80	0.0027	36.20

Table 23. Model accuracy and precision for the December 2002 water quality model (* not normally distributed, ^x outlier removed).

Variable	Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.80*	0.0010	2.75	0.80*	0.0010	2.75
DO	0.61	0.0130	20.63	0.62	0.0121	0.49
TON			20.54			14.71
NH ₃			4.72			1.35
NO ₂ NO ₃	0.92	<0.0001	5.38	0.92	<0.0001	6.62
TN			15.22			12.24
TOP			32.92			14.22
InorgP			190.01	0.62 ^x	0.0196	37.10
TP			34.16	0.81 ^x	0.0024	29.54
Chl <i>a</i>			10.48			7.23
TSS			17.7	0.78 ^x	0.0036	11.67

Table 24. Model accuracy and precision for the December 2001 water quality model.

Variable	Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity	0.96	<0.0001	7.81	0.96	<0.0001	7.81
DO			21.98			4.63
TON			47.66			47.65
NH ₃			6.37	0.61	0.0131	0.79
NO ₂ NO ₃	0.80	0.0012	33.55	0.83	0.0007	16.60
TN			30.3			29.56
TOP			5.75			1.39
InorgP	0.75	0.0026	20.72	0.82	0.0007	4.40
TP	0.74	0.0027	15.35	0.93	<0.0001	1.93
Chl <i>a</i>			1635.61			34.05
TSS			25.75	0.61	0.0135	25.74

Table 25. Model accuracy and precision for the April 2002 water quality model (^x outlier removed).

Variable	Initial Model			After Manipulation		
	r ²	P	Percent Mean Difference	r ²	P	Percent Mean Difference
Conductivity			6.23			6.23
DO			4.43	0.97 ^x	<0.0001	1.30
TON			76.63			84.99
NH ₃			13.72	0.45	0.0486	7.73
NO ₂ NO ₃	0.67	0.0070	3.26	0.67	0.0069	0.75
TN			1.02	0.79 ^x	0.0032	8.41
TOP			5.46			0.26
InorgP			15.58			10.47
TP			9.1			4.29
Chl <i>a</i>	0.52	0.0295	15.08	0.50 ^x	0.0326	4.00
TSS			19.26	0.61	0.0135	20.81

Table 26. Model accuracy and precision for the January 2003 water quality model.

Variable	Final Model		
	r ²	P	Percent Mean Difference
Conductivity	0.74	0.0028	1.17
DO	0.81	0.0010	5.49
TON			687.47
NH ₃	0.60	0.0144	38.60
NO ₂ NO ₃			4.77
TN			83.18
TOP			14.41
InorgP	0.62	0.0180	9.18
TP	0.44	0.0500	12.64
Chl <i>a</i>			5.42
TSS			73.97

Table 27. Rates, constants, and coefficients used to model the upper Assiniboine River during the four seasons (2001 to 2003).

Parameter	Units	Range This Study
Benthic Fluxes		
Sediment Oxygen Demand	gO ₂ /m ² /d	0 - 19
NH ₄ Flux	mgN/m ² /d	0 - 12
InorgP Flux	mgP/m ² /d	0 - 5
Stoichiometry:		
Carbon	mgC	40
Nitrogen	mgN	8.5
Phosphorus	mgP	1.4
Dry weight	mgD	100
Chlorophyll	mgA	1
Inorganic suspended solids:		
Settling velocity	m/d	0.0001 - 0.02
Oxygen:		
Reaeration model		Internal during Open Water and Prescribed 0.10/d during Ice Cover
Temp correction		1.024
O ₂ for carbon oxidation	gO ₂ /gC	2.69
O ₂ for NH ₄ nitrification	gO ₂ /gN	3.43
Oxygen inhib CBOD oxidation model		Exponential
Oxygen inhib CBOD oxidation parameter	L/mgO ₂	0.6
Oxygen inhib nitrification model		Exponential
Oxygen inhib nitrification parameter	L/mgO ₂	0.6
Oxygen enhance denitrification model		Exponential
Oxygen enhance denitrification parameter	L/mgO ₂	0.6
Organic N:		
Hydrolysis	/d	0.001 - 0.05
Temp correction		1.07
Ammonium:		
Nitrification	/d	0.1 - 0.75
Temp correction		1.07
Nitrate:		
Denitrification	/d	1 - 4
Temp correction		1.07
Sed denitrification transfer coeff	m/d	0
Temp correction		1.07
Organic P:		
Hydrolysis	/d	0.001 - 0.8
Temp correction		1.07
Phytoplankton:		
Max Growth	/d	2.5
Temp correction		1.07
Respiration	/d	0.15
Temp correction		1.07
Death	/d	0 - 0.25
Temp correction		1
Nitrogen half sat constant	ugN/L	20
Phosphorus half sat constant	ugP/L	5
Light model		Half saturation
Light constant	langleys/d	43
Ammonia preference	ugN/L	25 - 50
Settling velocity	m/d	0.03 - 0.1

Table 27. Rates, constants, and coefficients used to model the upper Assiniboine River during the four seasons (continued....).

Parameter	Units	Range This Study
Detritus (POM):		
Dissolution	/d	0 - 0.001
Temp correction		1.07
Settling velocity	m/d	0.001 - 0.1
Photosynthetically Available Radiation:		
Background light extinction	/m	0.47
Linear chlorophyll light extinction	1/m-($\mu\text{gA/L}$)	2 - 5
Nonlinear chlorophyll light extinction	1/m-($\mu\text{gA/L}$) ^{2/3}	0.0088
ISS light extinction	1/m-(mgD/L)	0.054
Detritus light extinction	1/m-(mgD/L)	0.052
Solar shortwave radiation model:		
Atmospheric attenuation model for solar		0.174
Bras solar parameter atmospheric turbidity coefficient (2=clear, 5=smoggy, default=2)		Bras
Downwelling atmospheric longwave IR radiation atmospheric longwave emissivity model		2
Evaporation and air convection/conduction wind speed function for evaporation and air convection/conduction		Brunt
		Brady-Graves-Geyer

Table 28. Seasonal fluctuations in benthic fluxes of NH_4 and inorgP in the four final models for the upper Assiniboine River (2001 to 2003).

Average	Winter	Spring	Summer	Fall
NH_4 Flux ($\text{mgN/m}^2/\text{d}$)	6.88	0.05	9.31	0.00
Inorganic P Flux ($\text{mgP/m}^2/\text{d}$)	0.36	2.34	3.10	1.67

Table 29. Relative contribution (%) of the four main sources of nutrients modelled in the upper Assiniboine River during each of the four seasons and compared to measured loads at Brandon (2001 to 2003).

Spring (1.4 m ³ /s)	Lake of the Prairies	Qu'Appelle River	Birdtail Creek	Little Saskatchewan River	All Three Tributaries	Incremental Inflows	Sediment Flux	Sediment and Incremental Inflows	Sources Exceed Measured Load at Brandon	Measured Load at Brandon exceeds Sources
Total Nitrogen	12.6	7.6	8.1	44.3	60.0	26.5	0.8	27.3	✓	✓
TON	12.8	7.7	8.2	44.7	60.5	26.7	0.0	26.7		✓
NH ₃	8.2	6.3	6.7	33.6	46.6	19.3	25.9	45.2	✓	
NO ₂ NO ₃	6.6	5.1	5.4	27.1	37.6	15.6	40.2	55.8	✓	
Total Phosphorus	4.9	9.6	9.7	17.6	36.9	22.4	35.8	58.2	✓	
TOP	9.2	16.9	11.6	29.2	57.7	32.3	0.8	33.1	✓	
InorgP	1.2	3.2	8.0	7.4	18.6	13.6	66.6	80.2	✓	
Summer (1.4 m ³ /s)	Lake of the Prairies	Qu'Appelle River	Birdtail Creek	Little Saskatchewan River	All Three Tributaries	Incremental Inflows	Sediment Flux	Sediment and Incremental Inflows	Sources Exceed Measured Load at Brandon	Measured Load at Brandon exceeds Sources
Total Nitrogen	9.2	8.8	0.3	4.9	14.0	37.7	39.0	76.7	✓	
TON	11.1	13.8	0.2	1.0	15.0	73.9	0.0	73.9		✓
NH ₃	7.7	5.1	0.4	7.6	13.1	12.6	66.6	79.3	✓	
NO ₂ NO ₃	14.8	14.1	0.5	5.4	20.0	40.7	24.5	65.2	✓	
Total Phosphorus	8.8	12.0	0.4	6.7	19.1	37.6	34.5	72.1	✓	
TOP	13.5	18.3	0.7	10.5	29.5	57.0	0.0	57.0		✓
InorgP	7.6	8.2	0.4	7.0	15.6	32.8	43.9	76.8	✓	

Table 29. Relative contribution (%) of the four main sources of nutrients modelled in the upper Assiniboine River during each of the four seasons and compared to measured loads at Brandon (continued....).

Fall (2.8 m ³ /s)	Lake of the Prairies	Qu'Appelle River	Birdtail Creek	Little Saskatchewan River	All Three Tributaries	Incremental Inflows	Sediment Flux	Sediment and Incremental Inflows	Sources Exceed Measured Load at Brandon	Measured Load at Brandon exceeds Sources
Total Nitrogen	47.5	4.2	1.7	31.3	37.2	16.0	-0.7	15.3	✓	
TON	44.4	4.0	1.7	30.4	36.1	19.5	0.0	19.5	✓	
NH ₃	59.4	4.9	1.2	37.6	43.7	0.0	-3.1	-3.1	✓	
NO ₂ NO ₃	75.2	7.1	2.8	23.3	33.2	0.0	-8.4	-8.4	✓	
Total Phosphorus	34.1	6.6	1.0	31.1	38.7	3.1	24.0	27.1		✓
TOP	42.2	9.0	0.9	24.3	34.2	23.6	0.0	23.6		✓
InorgP	32.9	6.2	1.0	32.2	39.4	0.0	27.7	27.7	✓	
Winter (2.8 m ³ /s)	Lake of the Prairies	Qu'Appelle River	Birdtail Creek	Little Saskatchewan River	All Three Tributaries	Incremental Inflows	Sediment Flux	Sediment and Incremental Inflows	Sources Exceed Measured Load at Brandon	Measured Load at Brandon exceeds Sources
Total Nitrogen	34.9	6.6	6.1	23.6	36.4	20.1	8.7	28.8	✓	
TON	45.9	2.4	5.1	29.2	36.7	17.4	0.0	17.4	✓	
NH ₃	28.2	3.0	5.7	22.5	31.2	7.6	32.9	40.5	✓	
NO ₂ NO ₃	21.3	19.8	8.7	13.8	42.2	41.6	-5.1	36.5		✓
Total Phosphorus	21.4	15.0	4.4	17.8	37.1	30.8	10.7	41.5	✓	
TOP	23.0	12.6	2.6	32.8	48.0	29.1	0.0	29.1	✓	
InorgP	21.0	15.7	4.9	13.4	34.0	31.3	13.8	45.0		✓



APPENDIX A

List of Water Chemistry Abbreviations

Abbreviation	Definition
Chl <i>a</i>	Chlorophyll <i>a</i>
DO	Dissolved oxygen
N	Nitrogen
TN	Total nitrogen
NH ₃	Ammonia
NH ₄	Ammonium
NO ₂ NO ₃	Nitrate-nitrite
DIN	Dissolved inorganic nitrogen
DON	Dissolved organic nitrogen
TON	Total organic nitrogen
TKN	Total kjeldahl nitrogen
P	Phosphorus
TP	Total phosphorus
InorgP	Inorganic phosphorus
DOP	Dissolved organic phosphorus
TOP	Total organic phosphorus
DP	Dissolved phosphorus
PP	Particulate phosphorus
TSS	Total suspended solids
ISS	Inorganic suspended solids
OSS	Organic suspended solids
POM	Particulate organic matter
C	Carbon
TC	Total carbon
TIC	Total inorganic carbon
TOC	Total organic carbon



APPENDIX B

River Hydraulic Model

Hydraulic geometry relationships for seven Water Survey of Canada and Manitoba Conservation gauging stations were developed by students at Red River College under the guidance of Mr. Ian Halket, Instructor, Red River College (Halket 2003). While the coefficients provide an excellent description of the hydraulic geometry at a wide range of discharge for the seven gauging stations, they do not provide an indication of the geometry for most of the 455 km reach of the upper Assiniboine River. For example, further examination of the hydraulic coefficients and the cross sections drawn for each station indicated that some gauging stations were situated in riffles (*e.g.*, Virden) while others were situated in pools (*e.g.*, St. Lazare). Therefore, a pattern of alternating pool and riffle sequences was derived for the Assiniboine River so travel times for a controlled release on September 24, 2001 from Lake of the Prairies to Brandon were consistent with those derived from the hydraulic model.

On September 24, 2001 at 11:45AM discharge from Lake of the Prairies was increased from 2.83 to 8.50 m³/s. During this period, discharge from the Qu'Appelle River, Birdtail Creek, and the Little Saskatchewan River were 0.55, 0.25, and 1.55 m³/s, respectively (Environment Canada 2003a and Surface Water Management Section 2003). An additional 1.12 m³/s was added along the 455 km to account for incremental inflows from precipitation runoff and small ungauged tributaries. Environment Canada Climate data (http://climate.weatheroffice.ec.gc.ca/Welcome_e.html) indicated some precipitation occurred (less than 10 mm total) during late September and early October at meteorological stations at Shoal Lake, Virden, and Brandon (Environment Canada 2003b). The time of travel of the leading edge of the wave of water was tracked as it moved downstream between Lake of the Prairies and the City of Brandon by looking at changes in water level and discharge at six gauging stations (Shellmouth Bridge, Russell, St. Lazare, Miniota, Griswald, Brandon at Grand Valley) (Bob Harrison and Melissa Hamilton, Water Branch, Manitoba Water Stewardship). Since these travel times represent the time of travel for the flood wave rather than the average velocity, travel times were multiplied by 1.67 to provide a measurement of average travel time in

a rectangular channel (Chow 1959). Time of travel-to each gauging station is presented in Table A1 and was used to calibrate the river hydraulic model.

Table A1. Travel times between gauging stations on the Assiniboine River.

Location	Time of leading Edge	Travel Time of Leading Edge in Hours	Days	Travel Time Based on Average Velocity (days)	Travel Time from 47 Reach Hydraulic Model (days)
Lake of the Prairies	2001-09-24 11:45		0		
Shellmouth Bridge	2001-09-24 16:00	4.25	0.18	0.30	0.31
Russell	2001-09-25 1:00	13.25	0.55	0.92	0.94
St. Lazare	2001-09-26 9:00	45.25	1.89	3.15	3.26
Miniota	2001-09-28 11:00	95.25	3.97	6.63	6.44
Griswold	2001-09-30 13:00	145.25	6.05	10.11	11.01
Brandon Grand Valley	2001-10-02 8:00	188.25	7.84	13.10	12.96

Given the general knowledge that the Assiniboine River contains a series of pool and riffle complexes, an alternating pool and riffle sequence was developed to divide the river into no more than fifty (the maximum number allowed for in the QUAL2E water quality model) individual pool and riffle sequences. Consequently, pools and riffles ranged from between 5 to 20 km long. Hydraulic coefficients for the pools and riffles were obtained from those derived for the gauging stations, and were initially assigned based on proximity to the gauging stations. Length and assignment of hydraulic coefficients were varied until travel times obtained by the hydraulic model were as close as possible to those obtained during the September 24, 2001 release (Table A1). After calibration, the Assiniboine River QUAL2E model consisted of 47 hydraulically distinct reaches. Table A2 describes the hydraulic coefficients at each of the 47 reaches along with the specific discharge scenario used for development of the model.

Inclusion of hydraulic geometry to describe both pools and riffles allows for a more genuine description of the physical parameters of the Assiniboine River such as width, depth, and water velocity. However, due to variations in physical characteristics, pools and riffles may also differ with respect to substratum type, particulate matter accumulation, and plant distribution. These differences can in turn impact nutrient recycling within the Assiniboine River and contribute to increased spatial nutrient heterogeneity. In fact, Meyer (1980) found significant differences between phosphorus dynamics in pools and riffles. Nitrogen removal by

denitrification and settling to bottom depends on water depth and discharge (Grizetti *et al.* 2003) such that pools of slow moving water may retain more nitrogen due to enhanced sedimentation and development of benthic organisms that are not swept away from their favoured habitat. Examination of nutrient vs. light limitation in the upper Assiniboine River with the final water quality model developed for summer also illustrated the importance of differences in physical changes between pools and riffles (Table A2). In deep pools, light limitation persisted throughout the day. Meanwhile in shallow riffles light was sufficient during the day and algal biomass became nitrogen limited during the hours of peak solar radiation. Differences in pool and riffle channel geometry may drive nutrient vs. light limitation across the Assiniboine River. Given the overall heterogeneity observed in the Assiniboine River, it is hypothesized that the 48 reach model is most appropriate for the upper Assiniboine River.

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Table A2. Change in nitrogen (N) vs. light limitation (L) in pool and riffle reaches between Lake of the Prairies and 280 km downstream during the summer final modelling period.

Distance from Lake of the Prairies (km)	Distance from Lake of the Prairies (km)																				280
	10	15	20	25	45	55	65	75	85	95	105	115	120	130	145	150	165	170	185	190	
Depth (m)	0.27	0.34	0.27	0.34	0.27	0.35	0.28	0.36	0.29	0.37	0.30	0.37	0.30	0.80	0.44	0.88	0.44	0.89	0.46	1.05	
Time of Day																					0.53
6:45	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
7:30	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
8:15	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
9:00	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
9:45	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
10:30	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
11:15	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
12:00	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
12:45	N	L	N	L	N	L	N	L	N	N	N	N	N	L	L	L	L	L	L	L	L
13:30	N	L	N	L	N	L	N	L	N	N	N	N	N	L	L	L	L	L	L	L	L
14:15	N	L	N	L	N	L	N	L	N	N	N	N	N	L	L	L	L	L	L	L	L
15:00	N	L	N	L	N	L	N	L	N	N	N	N	N	L	L	L	L	L	L	L	L
15:45	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
16:30	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
17:15	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
18:00	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
18:45	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
19:30	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
20:15	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
21:00	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

